COAL PLUG FEEDING - MATHEMATICAL MODEL (UP-E-175)

FINAL REPORT

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1.0 EXECUTIVE SUMMARY

A series of experiments on the characteristics of compacted coal were carried out to determine the effects of applied pressure, particle size, moisture content and sample size on the density, permeability, wall pressure and wall friction of the compacted plug within a cylindrical container.

The object of the study was to establish a rational base for the design of a continuous feeder for pressurized combustors.

The test results were analyzed and a suggested computational methodology was developed. The computation methodology is both theoretical and semi-empirical and has been influenced by previous researchers in the field of metal compacts. This study is expected to give reasonably correct trends for parameters affecting the design of future coal injectors on pressurized fluidized bed combustors.

2.0 RESUMÉ

Au but d'établir un base rational pour la planification d'un nourisseur continueux pour réacteurs sous pression, nous avons préparée un rapport, qui présente les résultats des expériences sur des caracteristiques du charbon sous pression. Les caracteristiques selectionnées pour experimentation été pression, grandesse des particules de charbon, grandesse de l'échantillon, et contenu de l'eau, et leurs effect sur la densité, la permeabilité, la pression sur le mur et la friction au mur.

Nous avons analysé les résultats et suggeré des algorithmes pour ordinnateurs. Le methodologie, ou théoretique ou demi-empiricale, été développée selon les résultats des chercheurs antérieurs dans le champ des métaux en poudre.

Au base de ces résultats nous pouvons donné des paramètres qui influence le planification des injecteurs de charbon pour combusteurs au lit fluide.

3.0 INTRODUCTION

This project was designed to address the art of continuous plug forming of various coal classifications. The principal effort was to create empirical mathematical models of selected physical characteristics of coal as they relate to a theoretical prototype coal feeding device for pressurized combustion and/or pyrolysis systems.

The principal physical characteristics investigated were moisture content and coal size and their relationship to crush strength, compaction energy, bulk density, gas permeability, mechanical dewatering capacity, friction factor and Poisson's Ratio.

Initial test results indicated a reasonable relationship to metal compacts technology and its mathematical modelling. The final results confirm this relationship and is therefore the premise of the mathematical modelling in this report.

Thanks to Harvey Boles, Manager of Costello Mine of MANALTA Coal Co. Ltd., Estevan, Saskatchewan for samples of lignite coal.

4.0 OBJECTIVES

The objective was to characterize lignite coal compacts formed by compressing various samples in a confined cylindrical walled vessel using a full bore piston under controlled loading conditions while recording primary data on forces, stresses, and gas flow rates through the compacts.

The primary data allows computation of the following relationships:

1. Crush strength vs. plug density
2. Wall pressures vs. unit compression forces
3. Plug length vs. wall friction
4. Void volume of the plug
5. Plug length vs. permeability
6. Plug density vs. gas permeability of the formed plug at various water contents in the coal sample
7. Water content vs. gas permeability
8. Plug density vs. structural integrity of the plug
9. Containment vessel angle vs. gas permeability
10. Dewatering rate vs. unit compression forces
11. Dewatering effect on wall area permeability
12. Displacement/HP relationship

5.0 EXPERIMENTAL TECHNIQUE

Weighted samples of lignite were placed in the tubular sections of the test apparatus followed by insertion of the piston. Load was applied to the piston upper surface by the compression head of a Tinius Olsen press. The loads were divided into 15000 kPa increments up to a maximum value of 75000 kPa.

Samples were divided by screening into the following mesh sizes - over 20mm, under 20mm but over 10mm, pass 10mm, pass 6mm. In addition samples of the various sizes were dried in an oven at 90°C to reduce the moisture content.

The strain/force data was determined in a 50mm diameter tube 300mm long, open at both ends. A disc, equipped with a strain gauge, was inserted in the bottom orifice of the vertically mounted tube. The top orifice allowed for the loading of the internal volume with lignite of the chosen size and moisture content. The bottom 150mm were equipped with circumferential strain gauges at 50mm intervals. Once the piston was inserted into the top orifice and load applied, the piston applied force, the bottom strain and the circumferential strains were recorded.

The circumferential strain versus load will indicate Poisson Ratio of the lignite compacts. A force-balance diagram of the applied force on the piston less the reaction force on the bottom disc will indicate the wall friction of the lignite compact.

Gas permeability was determined in an 87.63mm diameter tube 300mm long with the upper orifice open and the bottom orifice flanged to allow nitrogen gas delivery to the bottom surface of the lignite compacts. The gas orifice in the attached blind flange was covered with a 5mm thick metal pot cleaner to allow for distribution of the nitrogen gas.

Lignite compression by the top inserted piston (87.00mm diameter) was initiated in 15000 kPa increments up to a maximum of 75000 kPa. At each load increment nitrogen gas was applied at a range of gas pressures from two fixed volume gas cylinders so as to determine the time required to achieve a pressure differential in the fixed volume gas vessels. Nitrogen gas pressures up to 4000 kPa were used to record the gas leakage (permeability) rate through a range of lignite bulk densities.

6.0 RESULTS AND MATHEMATICAL MODELLING

All the objectives set out in section 4.0 have been met, mostly in considerable quantitative detail. Some parameters proved impossible to quantify. The formed plugs were always so frangible as not to allow meaningful mechanical testing for stress and strain.

In other areas early experiments showed that certain parameters had such slight effects, if any, that more detailed investigations were not appropriate. One example is the effect of divergence angle on gas permeability. The main results, together with appropriate mathematical models are presented.

Detailed measurements are presented in graphical form in the Appendix.

6.1 CRUSHING FORCE VS. PLUG DENSITY

On a log-log plot all experiments have yielded a straight line with very small variance.

Writing F_C for applied crushing force, D_I for bulk (ideal) density of coal, and D_A for apparent density of sample, then the appropriate model is:

(6.1.1) $$D_A/D_I = D_O P^C$$

The exponent, c, is relatively constant, with a mean value of 1.29 (range 1.10 to 1.39).

The constant of proportionality, D_O is dependent on plug length and may also be dependent on plug diameter. With a 50mm diameter cylinder, parameter D_O varies between 5 and 20, with the smaller values corresponding to the greater plug lengths.

Equation 6.1.1 therefore can be rewritten as

(6.1.2) $$D_A/D_I = D_O P^{1.29}$$

In the experiments the maximum force applied was 13500 kg (75000 kPa). At this load the density of the longer plug was considerably less than that of solid coal, typically reaching a value of about 40%. The plugs with smaller height to diameter ration approached 80% of the density of solid coal.

There is no clear correlation between the particle size of the initial sample and the degree of compaction obtainable. There was some indication that samples which were rejected by a 20mm sieve started at higher density (i.e. the line on the graph was higher) and so achieved a somewhat higher final density. This was not statistically significant, however, but is not unexpected, since a sample containing relatively large amounts of uncrushed fragments should have a lower void volume and hence a higher initial density.

6.2 WALL PRESSURE VS. COMPRESSIVE FORCE

This is one of the factors measured directly by placing strain gauges on the wall. The conversion of strain readings to wall pressure was according to thick wall cylinder theory. The derivation is given in the appendix.

The wall pressure is a linear function of the applied pressure.

(6.2.1) $$Pw = C + DPa$$

In the test the constants C and D seem to be functions of sample weight and are relatively independent of particle size or moisture content.

The tests also show considerable hysteresis in the heavier test samples (=250 grams). The lightest test samples (=150 gms) showed little or no hysteresis.

These results indicate that the wall pressure is highly dependent on geometry of the tube and the specimen. In addition, the results may be sensitive to location of the strain gauge with respect to the compressed coal plug. This would be in line with powder metallurgy data indicating that wall pressure is not uniformly distributed throughout the compressed sample.

It should be noted that the light test samples (150gms) compressed to L/D = 1, the heavier samples (250 gms) compressed to L/D = 2.

It can be concluded from these tests that wall pressure at any point is a linear function of the applied pressure and that sufficiently large specimens will have considerable residual wall pressure after the applied load is relieved.

6.3 PLUG LENGTH VS WALL FRICTION

The wall friction is due to the induced wall pressure. The total friction force on the walls can be derived from the compressive force on the top and the reaction force on the bottom of the plug (tests 1/31/02, 1/31/03, 1/31/04). These are generally straight line functions.

F_A = applied, F_B = bottom force

(6.3.1) $$F_B = M + N F_A$$

where M and N are constants dependent on plug composition.

The friction force F_f is then

(6.3.2) $$F_f = F_A - F_B = -M + (1-N)F_A$$

(Note: In test results M is always a negative number)

Further, the wall friction in terms of the wall pressure can be written.

(6.3.2) $$F_f = f(\pi dh)P_w$$

d = plug diamater, h = plug height, f = coefficient of friction

The friction force is also responsible for the breakaway force. It should be noted that in the applied force/bottom force charts there is a marked difference in the loading and unloading forces. This is due to the residual friction force, which can be a substantial amount.

Comparing the zero intercept at unloading will give some measure of the wall friction.

Analyzing the force/balance data it is obvious that the lower the bottom force the greater is the wall friction.

Generally, in tests with 250gm speciments the bottom forces were significantly lower than those with 150gm specimens.

The total resistant force due to friction accumulates with column length at any one specific density.

The longer the column and the greater the density, the higher the friction.

There are not sufficient tests within one weight category of any one parameter, to have strong indicators. There are some general trends that have been observed.

6.4 VOID VOLUME OF PLUG

The proportional void volume may be obtained directly from the data on bulk density.

(6.4.1) $$V_V = 1 - (D_A/D_I)$$

where V_V is the proportion of the sample occupied by void and D_A/D_I is the density of the sample normalized to the bulk/ideal density of coal (D_I).

When the coal sample is first loaded into the sample chamber its void volume is high, ranging from 49% to 81% of the total sample. After applying a crushing force of 13,500 kg (75000 kPA) V_V typically had a value of 60%, with a range of 19% to 68%.

Despite the high void volume, efficient wall seals against gas leaks are obtainable with these coal plugs. The greatest part of the voids must therefore be in the form of extremely fine capillary channels with abundant dead-ends, and a comparatively low percolation factor.

6.5 PLUG LENGTH VS. PERMEABILITY AT CONSTANT DENSITY

The permeability of a formed plug is a weak exponential function of the length of plug. In other words, on a log-linear plot, the function forms a more or less straight line. A plug four times as long is thus twice as impermeable.

6.6 PLUG DENSITY VS. GAS PERMEABILITY OF THE FORMED PLUG

This requires an expression for gas permeability as a function of plug density for different water content.

Plug density can be expressed:

$$\frac{D_A}{D_I} = C + Ps \tag{6.6.1}$$

P = applied pressure, s = constant for coal, C = constant function of water content and particle size, B = constant, k = constant, A = area, T = time, D_A = actual density, D_I = ideal density, U = permeability, = 1/TA

Permeability, U, =

$$\frac{1}{TA} = B.\exp(kP) \tag{6.6.2}$$

which suggest that

$$\ln U = \ln B + kP \tag{6.6.3}$$

$$\frac{\ln U - \ln B}{k} = P \tag{6.6.4}$$

$$\left(\frac{D_A}{D_I} - C\right)^{1/s} = P = \frac{\ln U - \ln B}{k} \tag{6.6.5}$$

$$\frac{\ln U - \ln B}{k} = D \tag{6.6.6}$$

leading to the general form

$$U = B.\exp(D_A/D_I - C)^{1/s} \tag{6.6.7}$$

6.6 Continued

Permeability was measured by applying nitrogen gas pressure (4000 kPa) to the back of a formed plug and measuring the time taken to drop a predetermined amount. In the graphs presented in the appendix the time for a drop in pressure is plotted against the pressure applied in forming the plug.

Up to about 50,000 kPa all plugs were moderately permeable, allowing a pressure drop in 20-30 seconds. Above that pressure of formation, samples containing a random range of sizes continued to be permeable. In particular the presence of particles over about 15mm produced a permeable plug.

By contrast, a sample made up of sieved particles less than 6mm (eg. test 1/19/1) showed a great decrease in permeability at formation pressures above 50000 kPa, showing times of several hundred seconds for the pressure drop. These pressures of formation correspond to densities of about 55% of the density of bulk coal. In the notation adopted here, in samples consisting entirely of small particles (less than 6mm), effective sealing against gas leaks is obtained when D_A/D_I is greater than 0.55, or when P_A is greater than 55000 kPa.

6.7 EFFECT OF WATER CONTENT ON GAS PERMEABILITY

In section 6.6 the relationship between plug density, particle size and permeability was explored. An effective seal was obtainable with fine-sieved moist coal if D_A/D_I was greater than 0.55, a density obtained at pressures of formation of the plug greater than about 55000 kPa.

The same was not true of dry coal (dried to constant weight at 90°C). At all densities and particle sizes plugs made from dry coal show rapid gas pressure drops, of the order of 20 secs. Even the highest pressures of formation (75000 kPa) did not lead to the formation of an effective seal.

It is clear that a large part of the impermeability of a moist coal plug is a result of capilliary forces of the water contained in a multitude of fine channels between the coal particles. Only when compression of the plug has reached the level at which the effective diameter of the capilliaries has been reduced to the point where the capilliary forces exceed the gas pressure throughout the whole system of pores, does the plug form a good seal.

A good seal is only obtainable with coal containing some liquid, which can be held in the pores by capilliary forces.

Tests on coals containing intermediate amounts of water, indicate that between 1 and 5 percent water content would be adequate to form an acceptable seal.

6.8 STRUCTURAL DENSITY VS. STRUCTURAL INTEGRITY OF THE FORMED PLUG

In these tests no simple quantitative test was possible to measure structural integrity of the compressed plug. Observation of the plugs showed that even if the plugs retained their shape while being pressed out the free standing plugs crumbled under the smallest load. It was observed that in the compression process some of the larger particles were broken down into smaller ones but in no case was there sufficient cohesion among the particles that particle size could be considered to have increased.

It is therefore obvious that at the pressures used in these tests bonding of the particles beyond simple interlocking did not take place.

Even at the highest pressures attained the formed plug has little structural integrity, especially at larger diameters. A 50mm plug is often firm enough to be handled gently without disintegration. A plug of 88mm diameter always crumbles when handled however gently. No quantitative data is available on this question.

Not unexpectedly, there appears to be a boundary effect influencing the structural integrity of the plug. Since the smaller plug is more coherent than the larger it is assumed that adhesion in the circumferential boundary is the major factor in plug integrity, and that an even larger plug will show still less integrity. As a result it is suspect that the centre of such a plug will prove more permeable to gas than the more cohesive boundary layer. This suspicion remains to be tested.

6.9 DIVERGENCE ANGLE VS GAS PERMEABILITY

The initial series of permeability trials were tested on a cylinder with an eight minute angle of divergence. Since the divergence angle did not prove any benefit on the effect of permeability it was decided to accentuate the use of the parallel sided tube for all remaining tests.

The divergence angle did facilitate the extraction of the coal compact. Comparison of coal compacts with straight walled cylinders versus tapered cylinders does reinforce the conclusion that wall leakage does not exceed the gas flow through the compacted lignite coal.

6.10 DEWATERING RATE VS. UNIT COMPRESSION FORCE

Using coal with a water content of 30-35%, water movement occurred under pressure. The data did not substantiate the derivation of a mathematical relationship.

Movement of water started visibly at 40,000 kPa. After this pressure was maintained for 40 sec. in a 50mm diameter cylinder, water began to appear at the periphery.

The tests indicate that with increasing moisture content the density ratio possible at any compacting force will be less.

6.11 DEWATERING EFFECT AND WALL AREA PERMEABILITY

Under pressures greater than 40,000 kPa water is forced to the periphery of the sample and may contribute to reducing permeability at the wall of the cylinder. This, however, is a minor effect, since the greater part of the permeation of gas is through the plug, not along the wall.

6.12 DISPLACEMENT/HORSEPOWER RELATIONSHIP

Total work can be regarded as made up of two parts, work of movement (W_m) and work of compression (W_c).

(6.12.1) $$W_T = W_m + W_c$$

W_m = friction force x distance moved

(6.12.2) $$= [-M.(1-N)F_A.Q].Np$$

where Q = distance moved per plug, and Np = number of stacked plugs.

(6.12.3) $$W_c = F_A \times L \times \tfrac{1}{2}$$

where L is the change in length of one plug and F_A is taken as the final measurement of the applied force.

The total work required to form and move one plug is thus

(6.12.4) $$W_T = [-M.(1-N)F_A.Q] \times Np + F_A \times L \times \tfrac{1}{2}$$

The static tests performed in this study do not enable us to quantify the parameters of this equation. Dynamic tests are required to establish dynamic friction values.

7.0 DISCUSSION

Continuous plug formation can in theory provide a means of stoking a pressurized combustion chamber or a pyrolysis system, provided the plug is sufficiently impervious to the gas pressure within the chamber. In this study a first attempt was made to parametize the major factors affecting plug formation of lignite coal, and the gas permeability of the plug, together with crush strength, mechanical dewatering capacity, friction factor and Poisson's ratio.

At the pressures used in the tests coal plugs were successfully formed at pressures less than 75000 kPa, plugs which have adequate wall seal and low permeability. Moreover, such plugs are very fragile, a point which is important for their disintegration as they enter a combustion chamber.

Plug formation was most effective, and the gas seal most efficient if the coal sample consisted of particles below about 6mm. It is apparent that pre-crushing of coal, rather than using the feeder to carry out crushing, would be more efficient in operating a pressurized combustion chamber.

A gas seal depends primarily on compression of the coal until the voids are reduced to capilliary dimensions. As a result, the seal is enormously improved by the presence of liquid (1-5%) held in these pores by capilliary forces. When the pores are fine enough for the capilliary force to exceed the gas pressure then the seal is effectively complete.

The Poisson's ratio is about 0.5, and a large part of the applied force is transmitted to the walls of the cylinder. The water contained within the boundary layer of the coal may serve to lubricate the wall and thus make more power available to displace the plug. Thus some water may be needed in the coal both to decrease permeability and to improve lubricity at the wall.

At the pressures used in these experiments water was expressed from the coal samples, providing some measure of mechanical dewatering. The rate of dewatering however was so slow as to be useless for commercial purposes.

8.0 CONCLUSIONS

As a result of an extensive test program, the following conclusions were reached:

1) There was no clear correlation between the particle size in the sample and the degree of compaction obtainable.
2) Larger sample quantities produced higher wall pressure hysteresis.
3) Wall friction appears to be a non-linear function of initial plug length.
4) In order to produce an impermeable plug, the maximum particle size of the sample must be less than 10mm.
5) Free water at levels of 1-5% readily produces an impermeable plug. Dry coal did not produce such a plug.
6) The plug which formed within the cylinder readily disintegrated as the material was pushed out of the containment tube.
7) The Poisson's ratio is a non-linear function of sample height.
8) There was no significant effect resulting from increasing cylinder taper, except that extrusion of the plug was easier in a flared cylinder.

9.0 RECOMMENDATIONS

It is recommended that an additional study be undertaken to evaluate key features which appear, from the results of the present study, to play a significant role in the design of a pressurized feeding system. These include the following:

1) Evaluation of local plug density variations, including microscopy.
2) Dynamic testing be utilized to augment the results of the present static evaluation.
3) That a relationship be determined between surface moisture (free moisture) and total moisture for different feedstocks. The surface moisture can then be evaluated for its effect on impermeability.
4) Evaluate the effect of precrushing on the overall energy required for feeding.
5) Determine whether particle reorientation occurs (as it appeared in one sample which was examined microscopically) as a result of compression.

STRAIN GAUGE APPARATUS

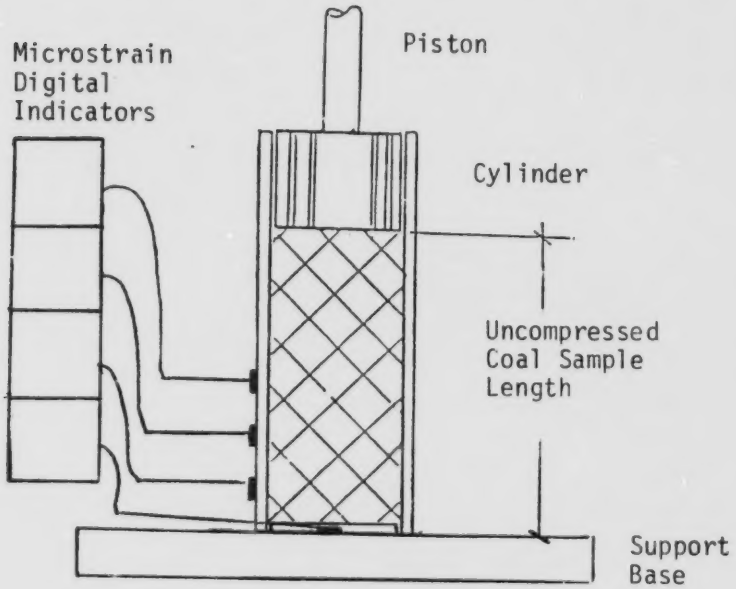
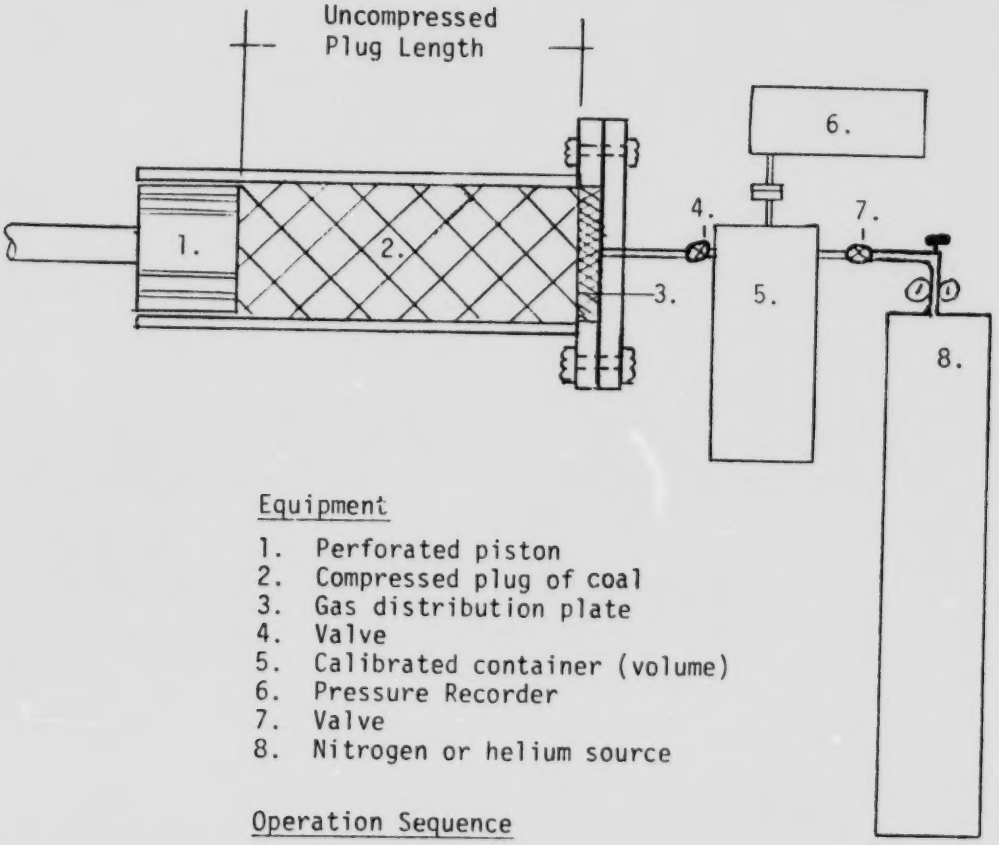


FIGURE 1

GAS APPARATUS



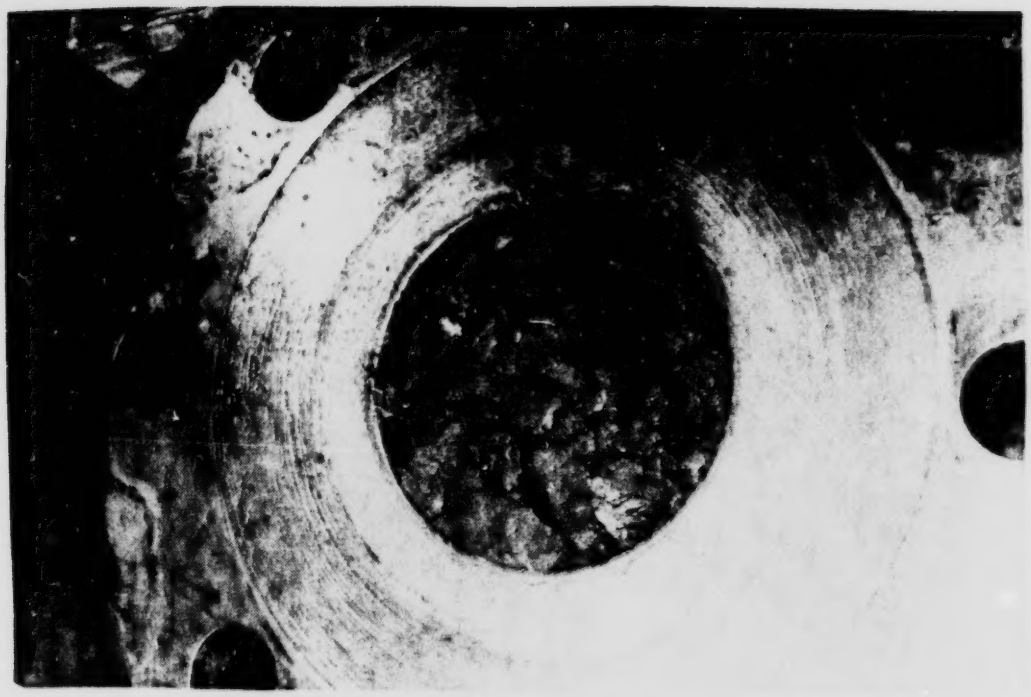
Equipment

1. Perforated piston
2. Compressed plug of coal
3. Gas distribution plate
4. Valve
5. Calibrated container (volume)
6. Pressure Recorder
7. Valve
8. Nitrogen or helium source

Operation Sequence

1. Close valve 4
2. Prepare compressed plug at selected piston force
3. Open valve 7 to fill container 5 to select pressure
4. Close valve 7
5. Open valve 4
6. Record pressure fall rate (minutes)

FIGURE 2

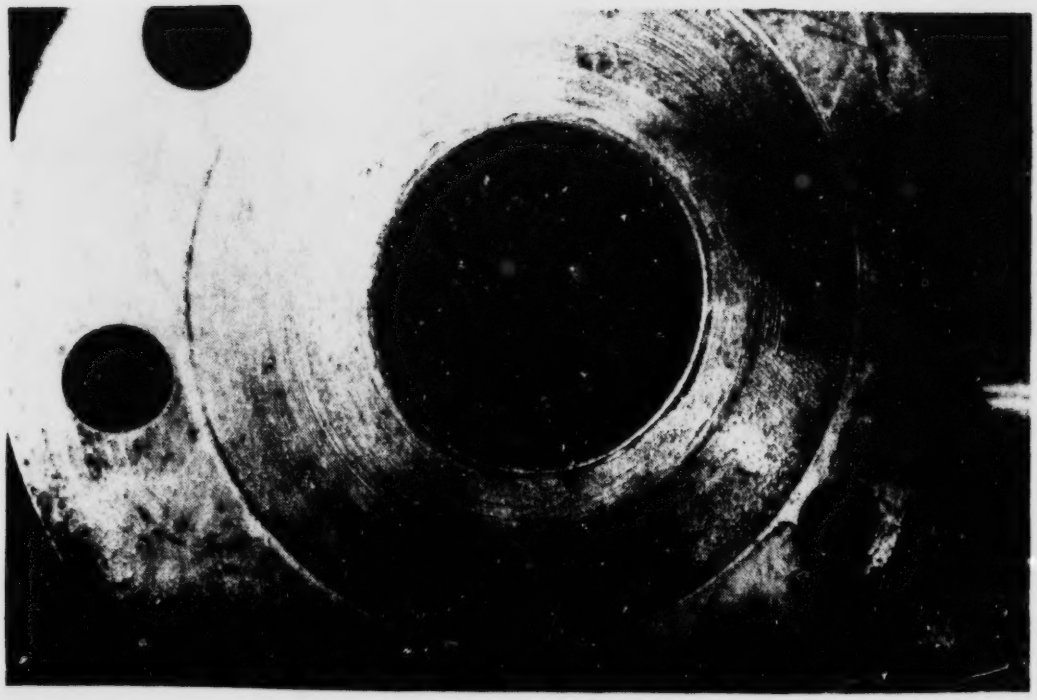


Pass 20mm, reject 6mm sample in compression tube

Pass 3/4, reject 3/16 sample following removal from tube

PERMEABILITY TESTS
ON LIGNITE COAL

Figure 3



Pass 3mm sample in compression tube

Pass 3mm sample after removal from tube

PERMEABILITY TESTS
ON LIGNITE COAL

Figure 4

Permeability Tests in Progress
on Lignite Coal

Figure 5

APPENDIX

NAME		DATE	Page
J. Kinslow	BBC ENGINEERING	FEB 7 1985	1 of 1

(REF.: DESIGN OF MACHINE ELEMENTS, SPOTTS 6TH ED.)

LAME EQUATIONS FOR THICK CYLINDERS

$$\left.\begin{aligned}\sigma_r &= C_1 + \frac{C_2}{r^2}\\ \sigma_t &= C_1 + \frac{C_2}{r^2}\end{aligned}\right\} \text{ AT ANY } r$$

SOLVING SIMULTANEOUSLY

$$C_1 = \frac{a^2 P_i - b^2 P_o}{b^2 - a^2}$$

$$C_2 = -\frac{a^2 b^2 (P_i - P_o)}{b^2 - a^2}$$

(NOTE @ r=a $\sigma_r = -P_i$

IN THE CASE WHERE $P_o = 0$, $P_i = P$

$$\sigma_r = \frac{a^2 P}{b^2 - a^2}\left(1 - \frac{b^2}{r^2}\right)$$

$$\sigma_t = \frac{a^2 P}{b^2 - a^2}\left(1 + \frac{b^2}{r^2}\right)$$

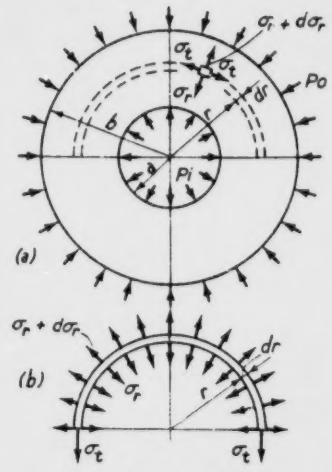


FIGURE 12-1 Thick-walled cylinder subjected to internal and external pressures.

WITH SINGLE STRAIN GAUGE MEASURING TANGENTIAL STRAIN "ϵ_t" ON THE OUTSIDE: $r = b$

$\sigma_r = 0$

$$\sigma_t = \frac{a^2 P}{b^2 - a^2}\left(1 + \frac{b^2}{b^2}\right) = \frac{2a^2 P}{b^2 - a^2}$$

BUT $\epsilon_t = \frac{1}{E}(\sigma_t - \mu\sigma_r)$ i.e. $\epsilon_t = \frac{\sigma_t}{E}$

$$\therefore \epsilon_t E = \frac{2a^2 P}{b^2 - a^2}$$

i.e. $$P = \epsilon_t \frac{E(b^2 - a^2)}{2a^2}$$

$$u_b = \epsilon_t \frac{(b^2 - a^2)}{2a}\left[\frac{1 + (a/b)^2}{1 - (a/b)^2} + \mu\right]$$

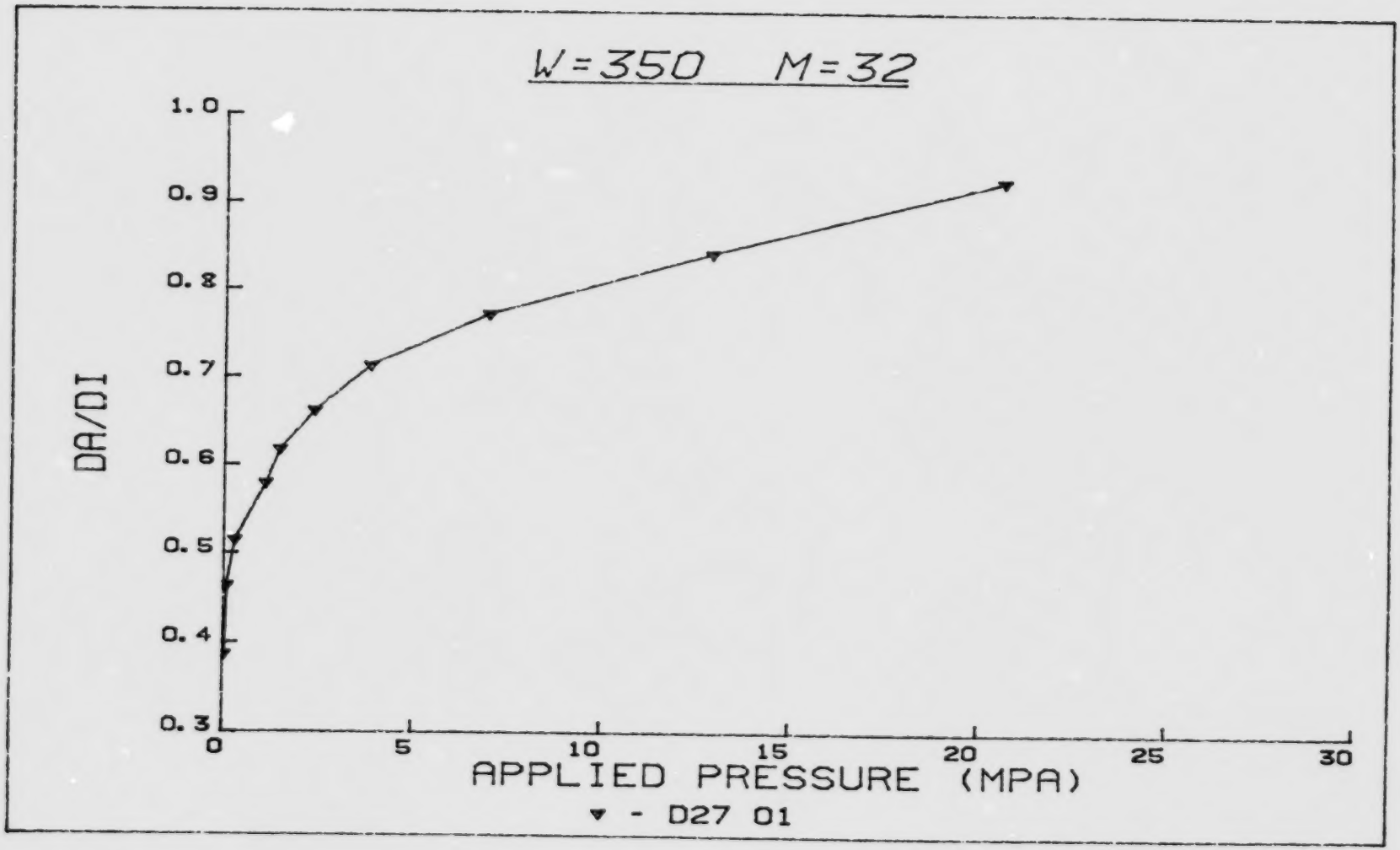
NOTE ALSO OF INTEREST: u_b = INCREASE IN RADIUS OF HOLE

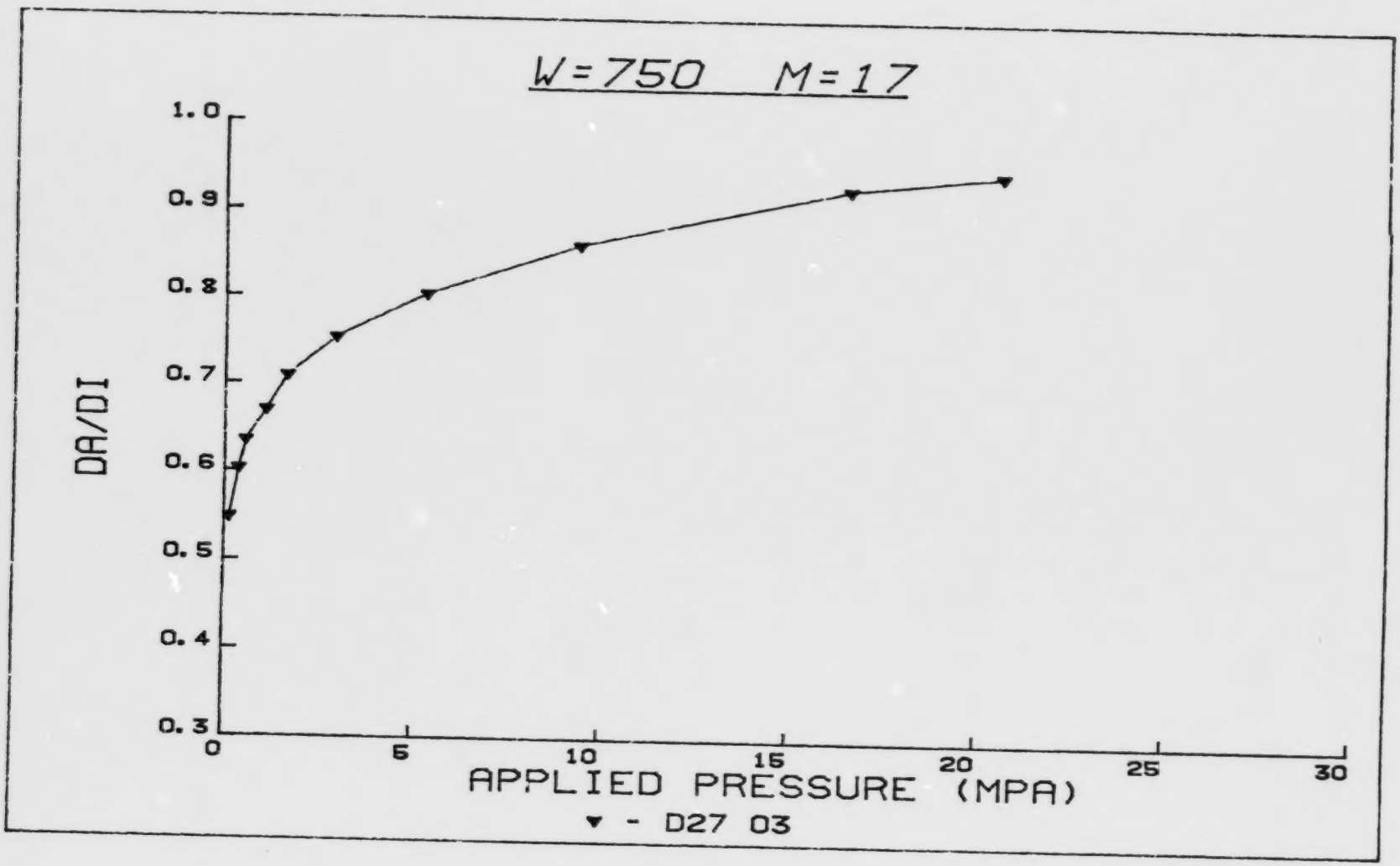
$$u_b = \frac{a}{E}(\sigma_t - \mu\sigma_r) = \frac{aP}{E}\left[\frac{1 + (a/b)^2}{1 - (a/b)^2} + \mu\right]$$

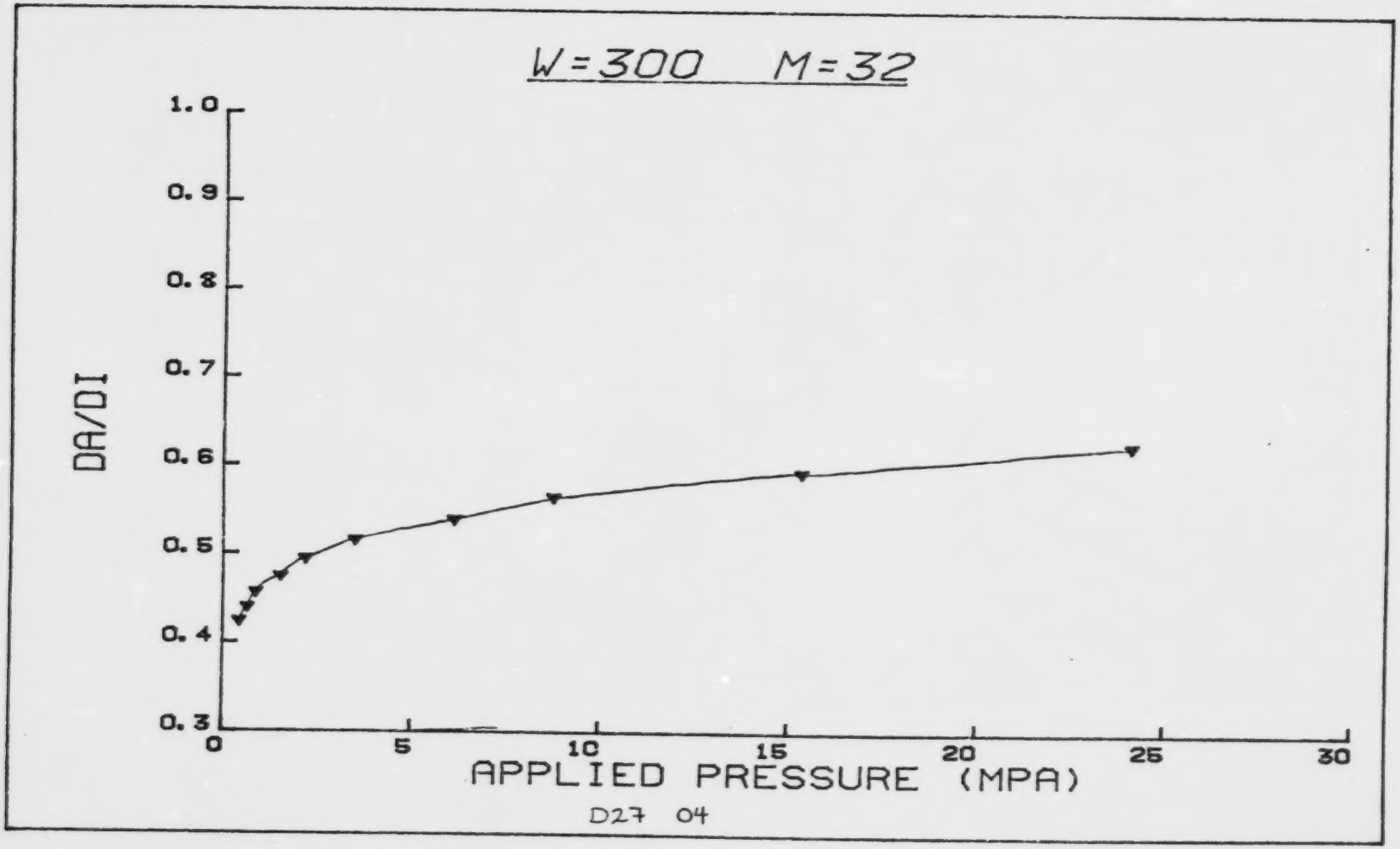
OR.

TYPICAL
DENSITY RATIO VS APPLIED PRESSURE CURVES

NS RECEIVED


W=350 M=32
1.0
0.9
0.8
0.7
0.6
0.5
0.4
0.3
DA/DI
0
5
10
15
20
25
30
APPLIED PRESSURE (MPA)
▼ - D27 01


W=750 M=17
1.0
0.9
0.8
0.7
0.6
0.5
0.4
0.3
DA/DI
0
5
10
15
20
25
30
APPLIED PRESSURE (MPA)
▼ - D27 03


W=300 M=32
1.0
0.9
0.8
0.7
0.6
0.5
0.4
0.3
DA/DI
0
5
10
15
20
25
30
APPLIED PRESSURE (MPA)
D27 04

bc

DENSITY RATIO VS APPLIED PRESSURE

(LOG-LOG)

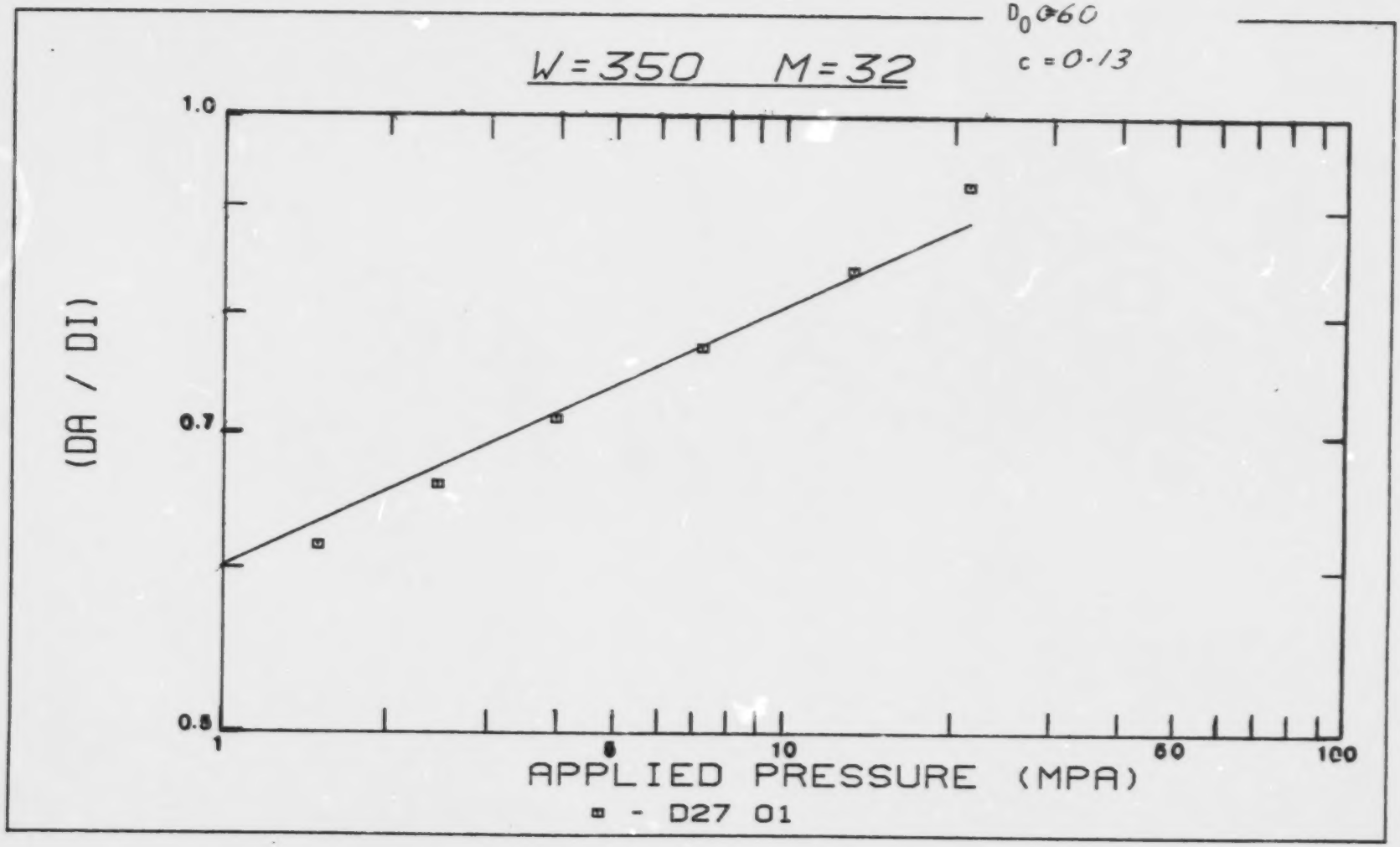
TUBE DIAMETER 880 mm

PARTICLE SIZE AS RECEIVED

$D_A/D_I = D_0 P^c$

D_0 @ 60

c = 0·13



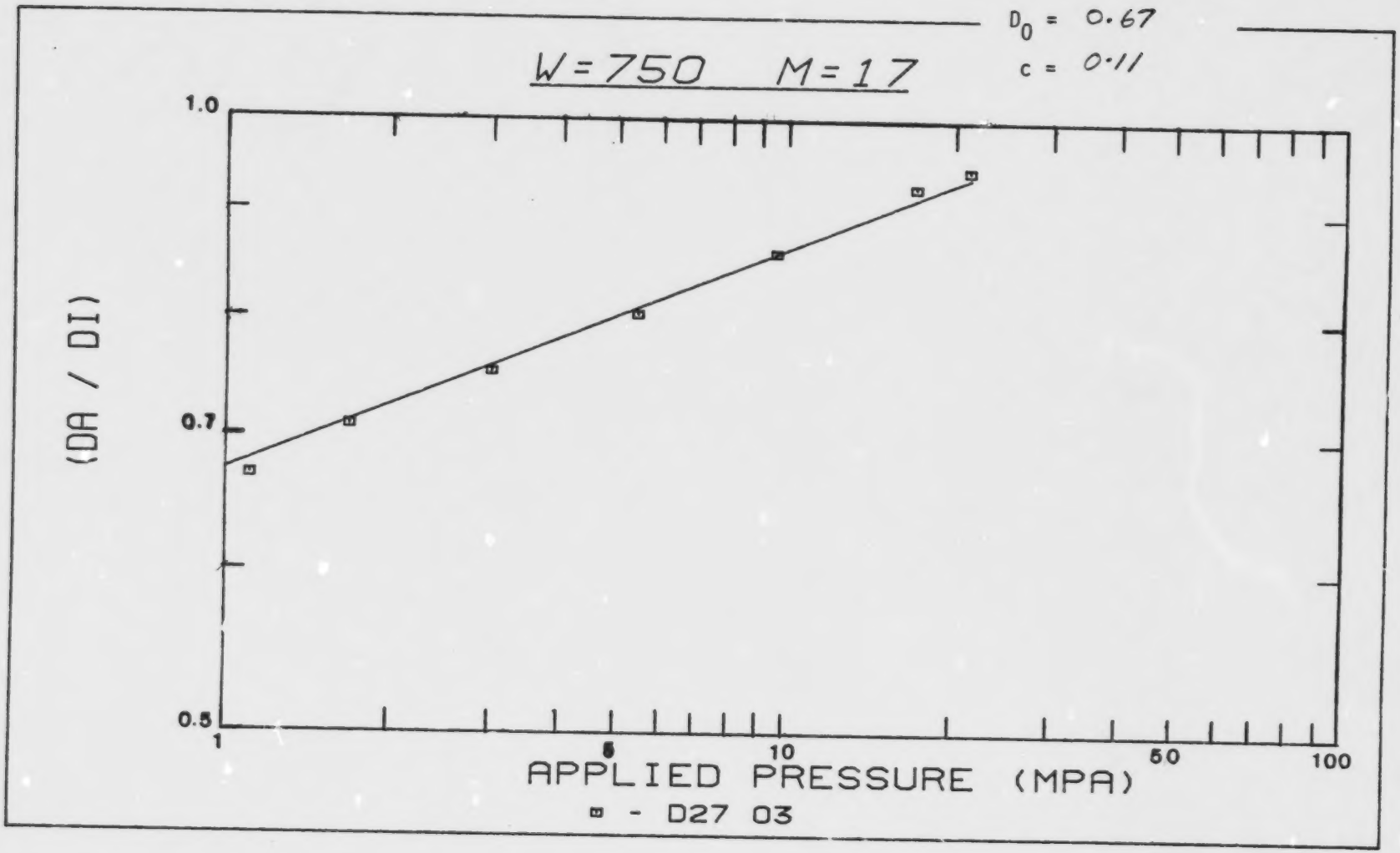
TUBE DIAMETER 880 TAPER

PARTICLE SIZE AS RECEIVED

$D_A/D_I = D_0 P^c$

$D_0 = 0.67$

$c = 0.11$



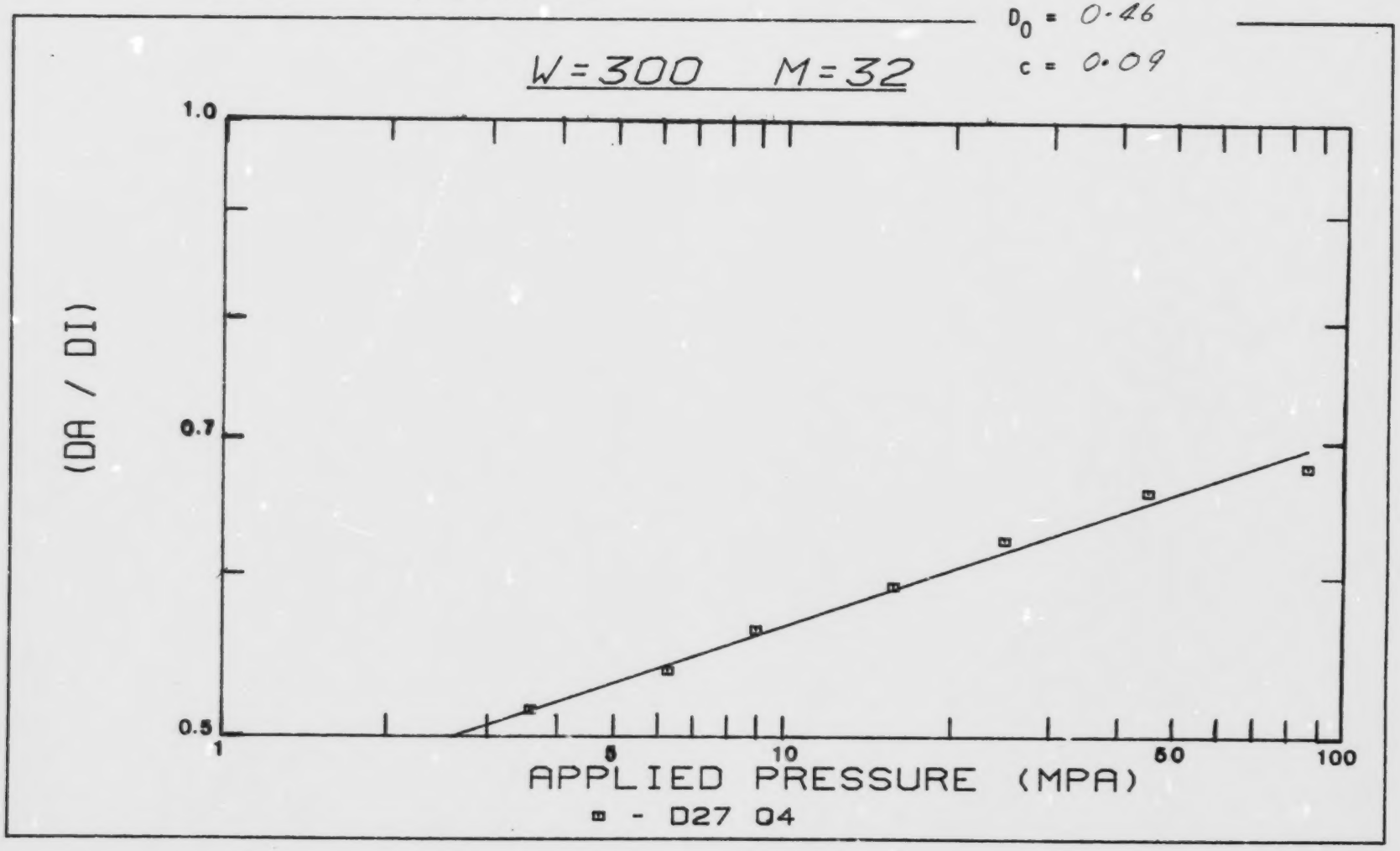
TUBE DIAMETER 500mm

PARTICLE SIZE AS RECEIVED

$D_A/D_I = D_0 P^C$

$D_0 = 0.46$

$c = 0.09$



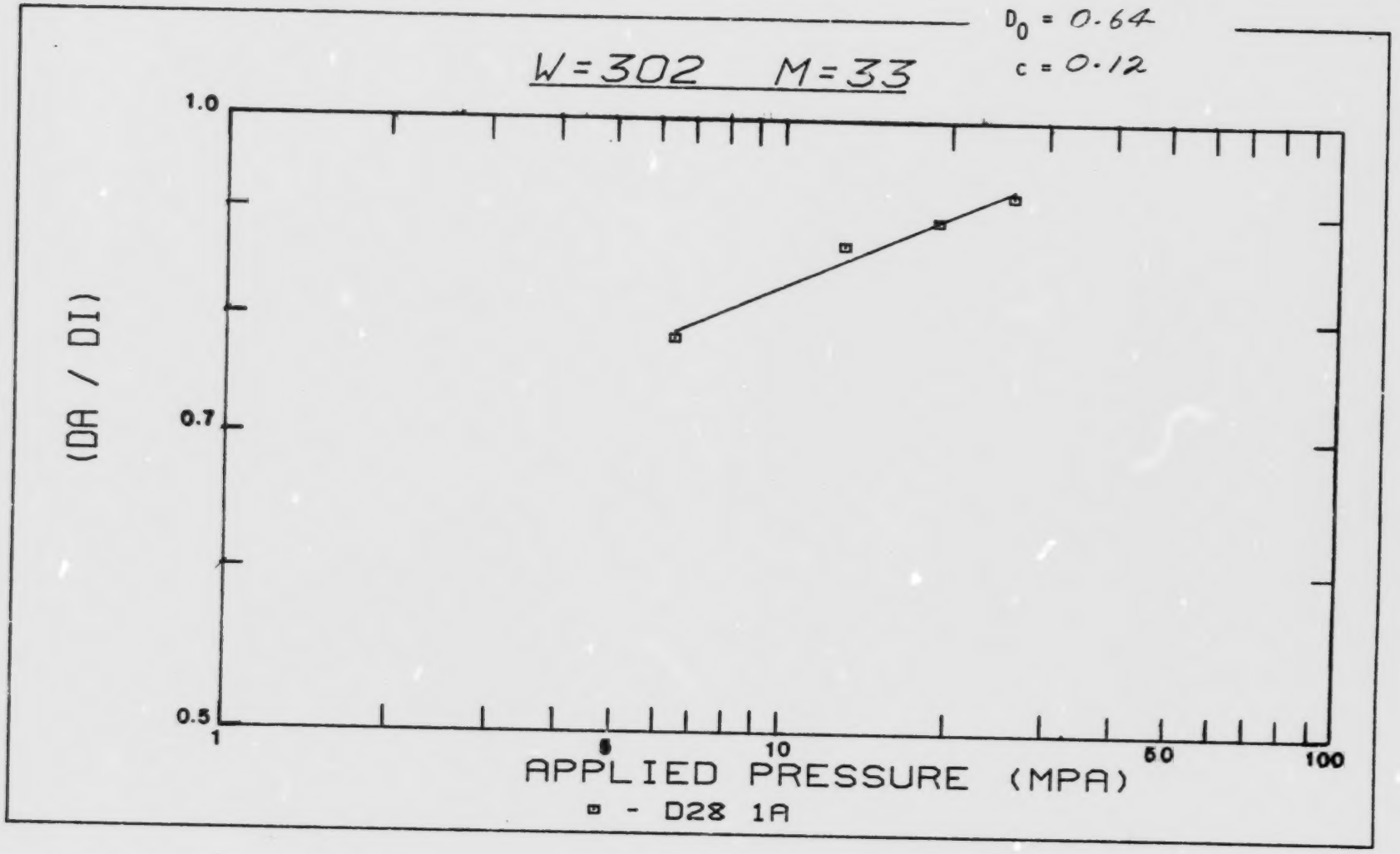
TUBE DIAMETER 880mm

PARTICLE SIZE AS RECEIVED

$D_A/D_I = D_0 P^c$

$D_0 = 0.64$

$c = 0.12$



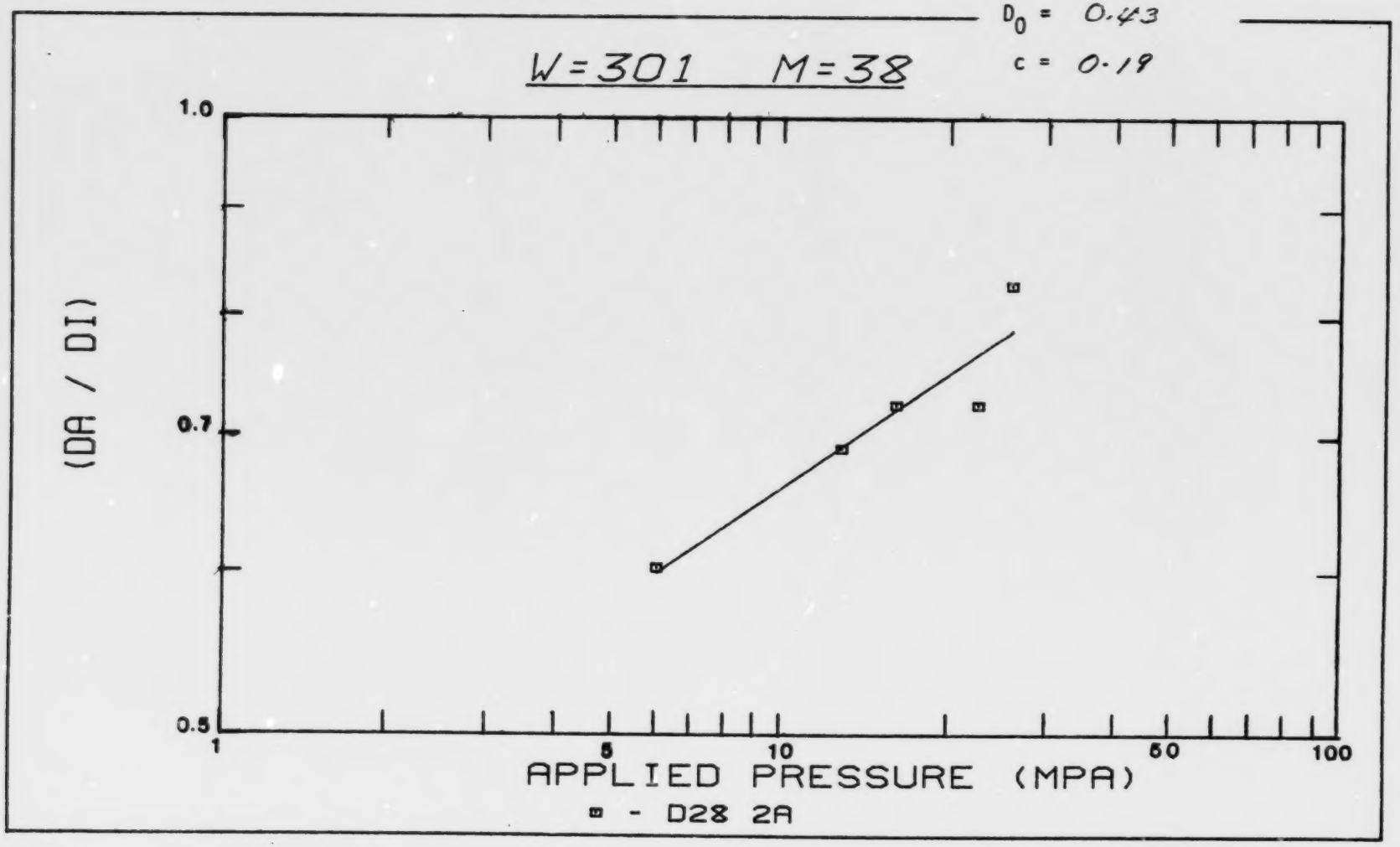
TUBE DIAMETER 880 mm

PARTICLE SIZE AS RECEIVED

$D_A/D_I = D_0 P^c$

$D_0 = 0.43$

$c = 0.19$



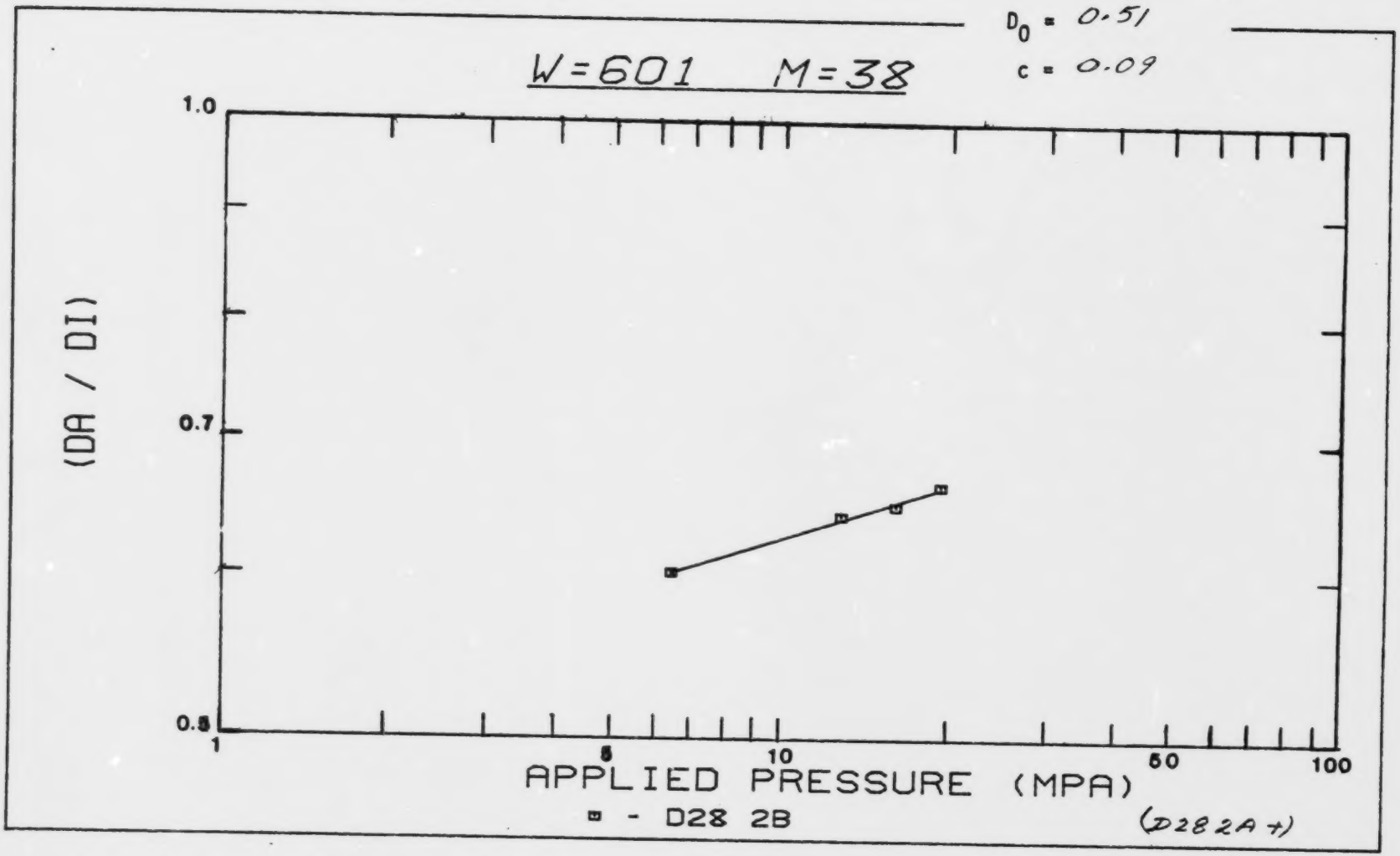
TUBE DIAMETER 800 mm

PARTICLE SIZE As Recived

$D_A/D_I = D_0 P^c$

$D_0 = 0.51$

$c = 0.09$



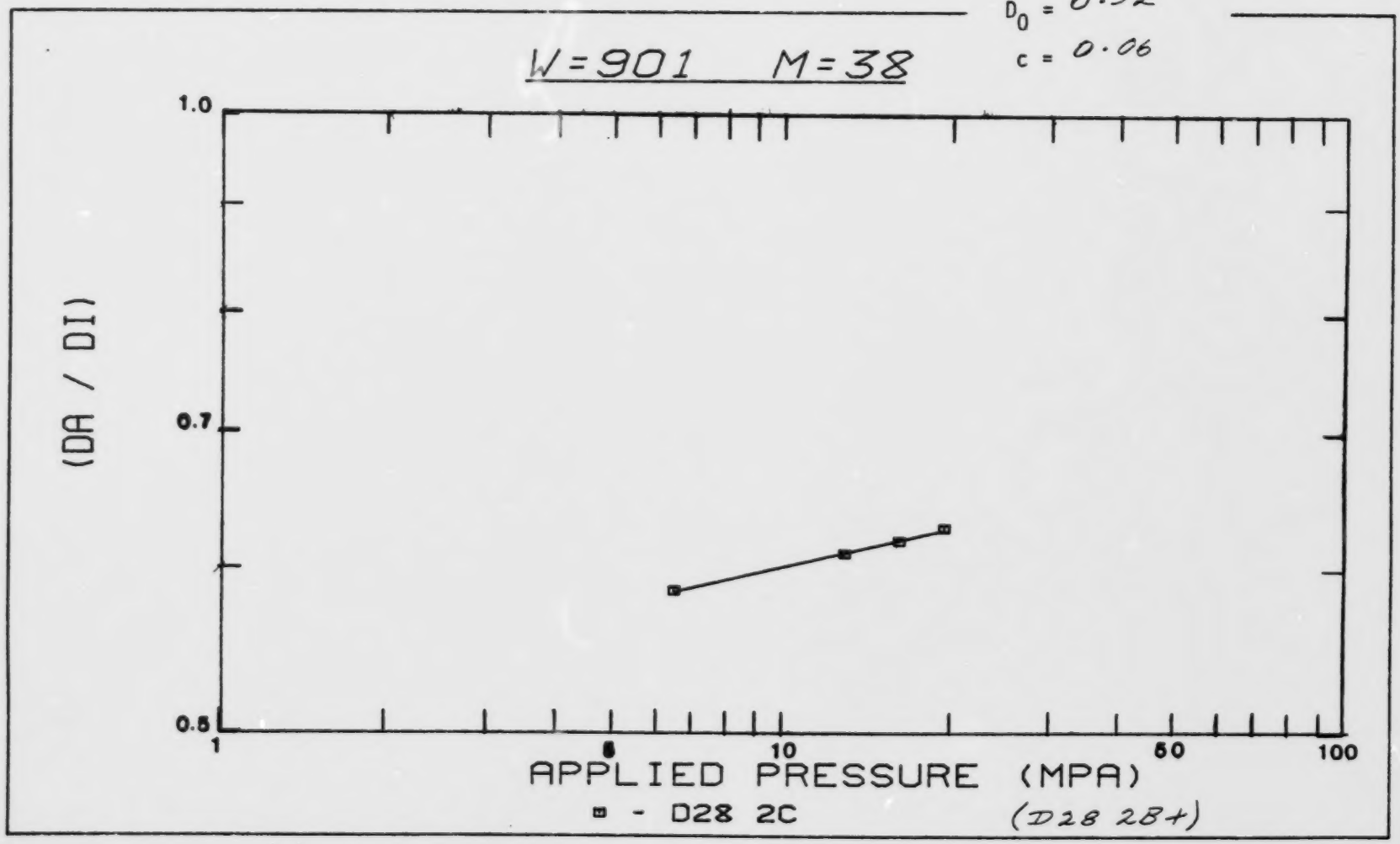
TUBE DIAMETER 88 mm

PARTICLE SIZE AS RECEIVED

$D_A/D_I = D_0 P^c$

$D_0 = 0.52$

$c = 0.06$



$Y = -0.282 + 0.0625 X$

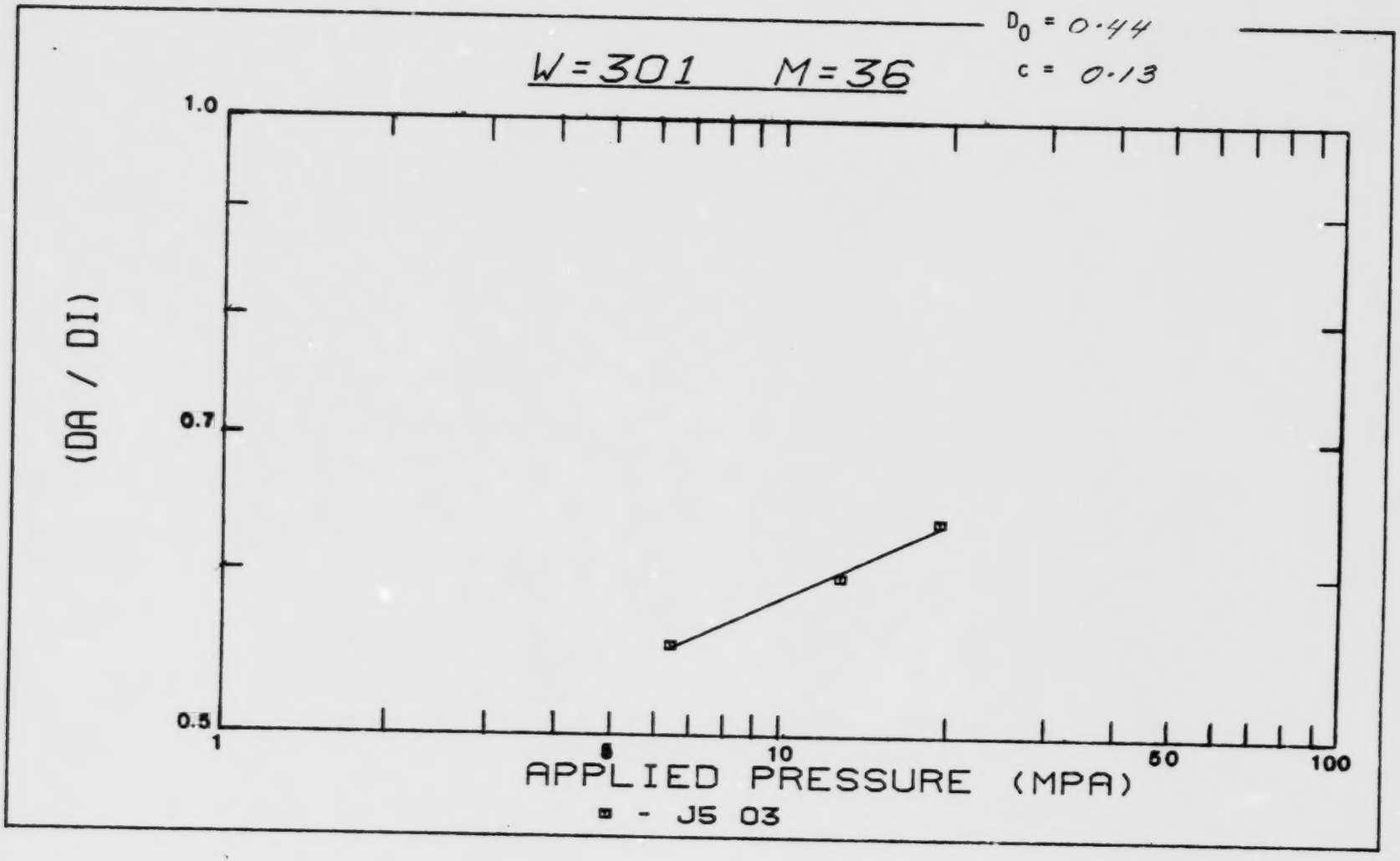
TUBE DIAMETER 880mm

PARTICLE SIZE < 4.76 mm

$D_A/D_I = D_0 P^c$

$D_0 = 0.44$

$c = 0.13$



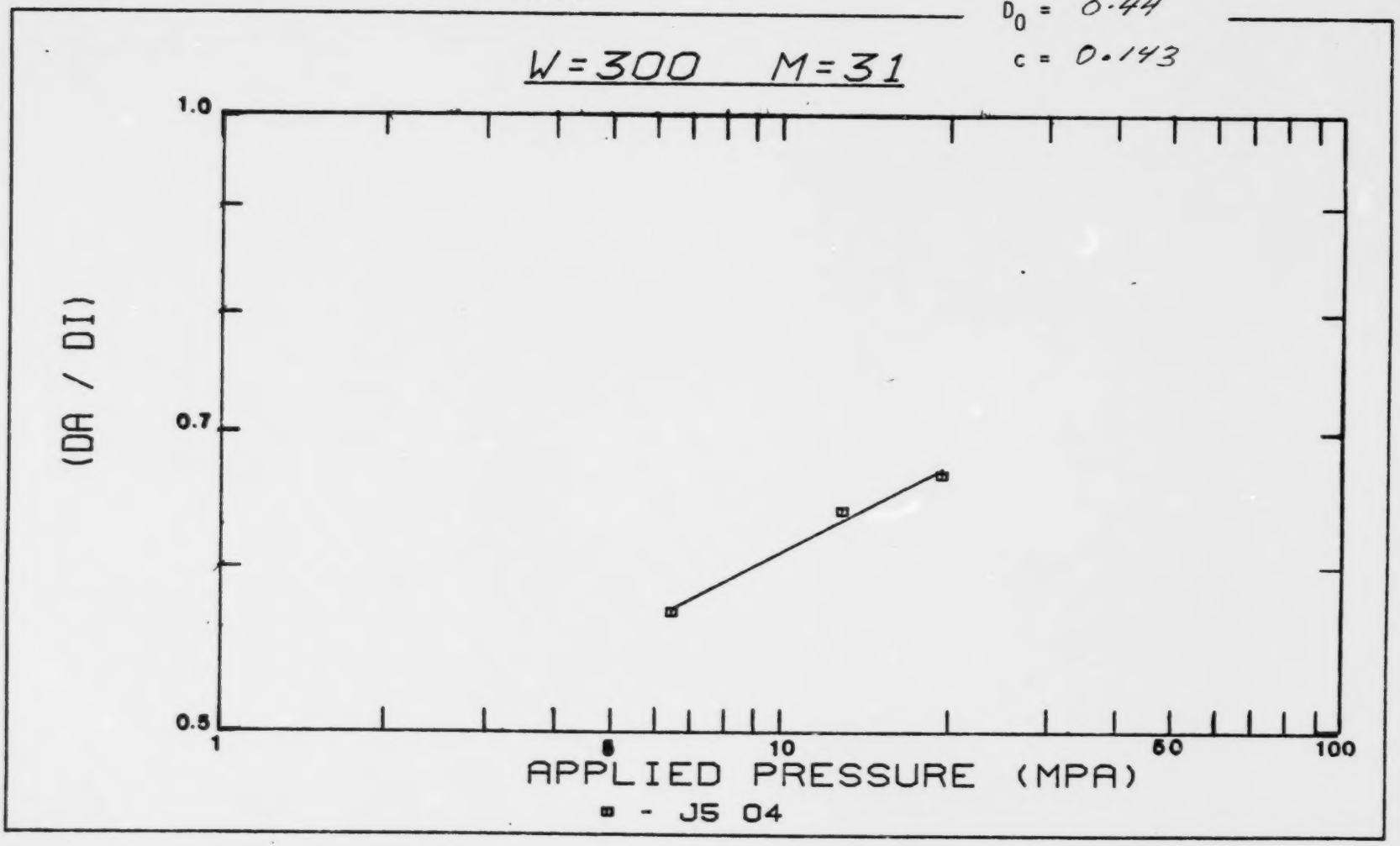
TUBE DIAMETER 880mm

PARTICLE SIZE < 3.17mm

$D_A/D_I = D_0 P^c$

$D_0 = 0.44$

$c = 0.143$



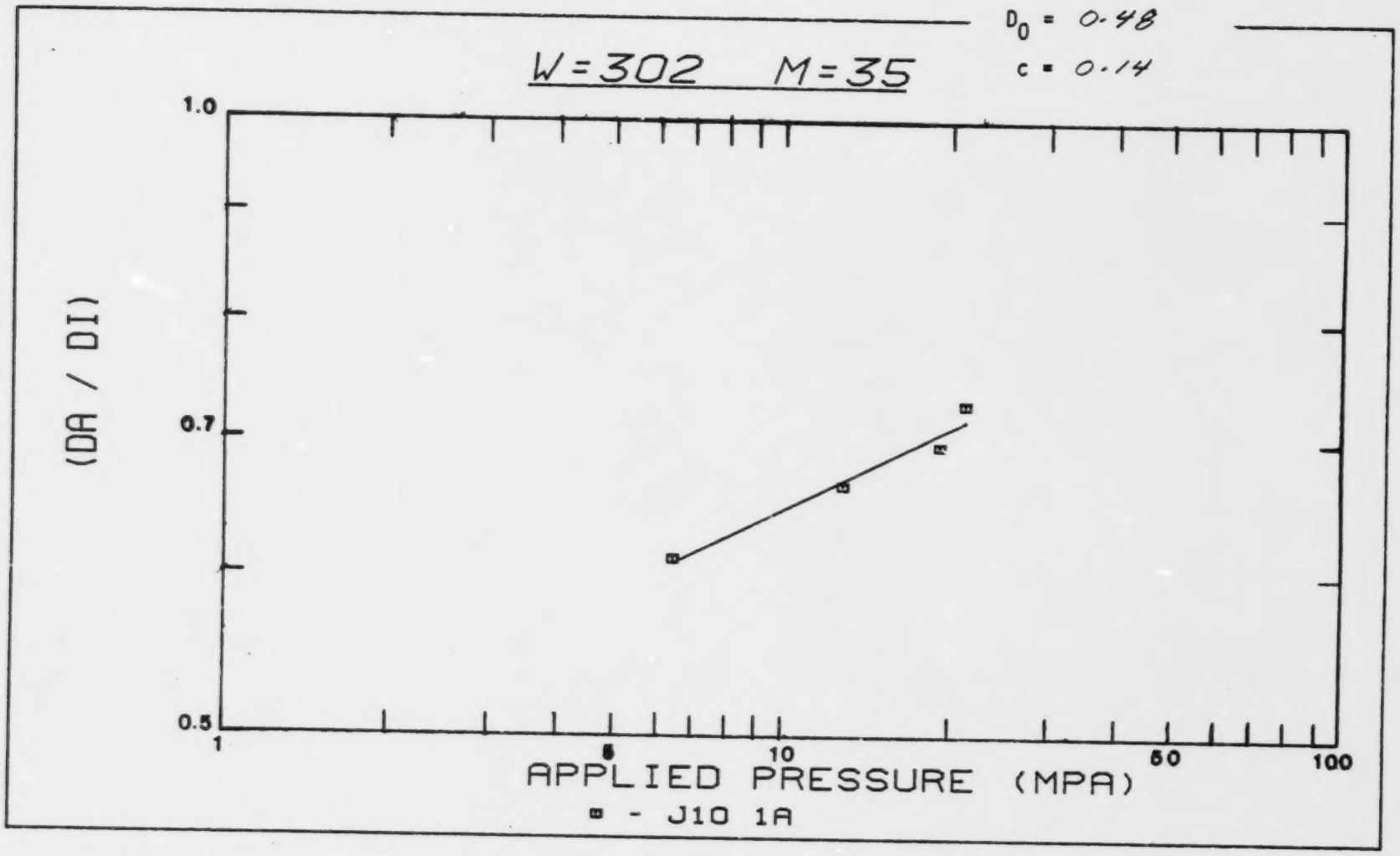
TUBE DIAMETER 880mm

PARTICLE SIZE >56.25

$D_A/D_I = D_0 P^C$

$D_0 = 0.48$

$c = 0.14$



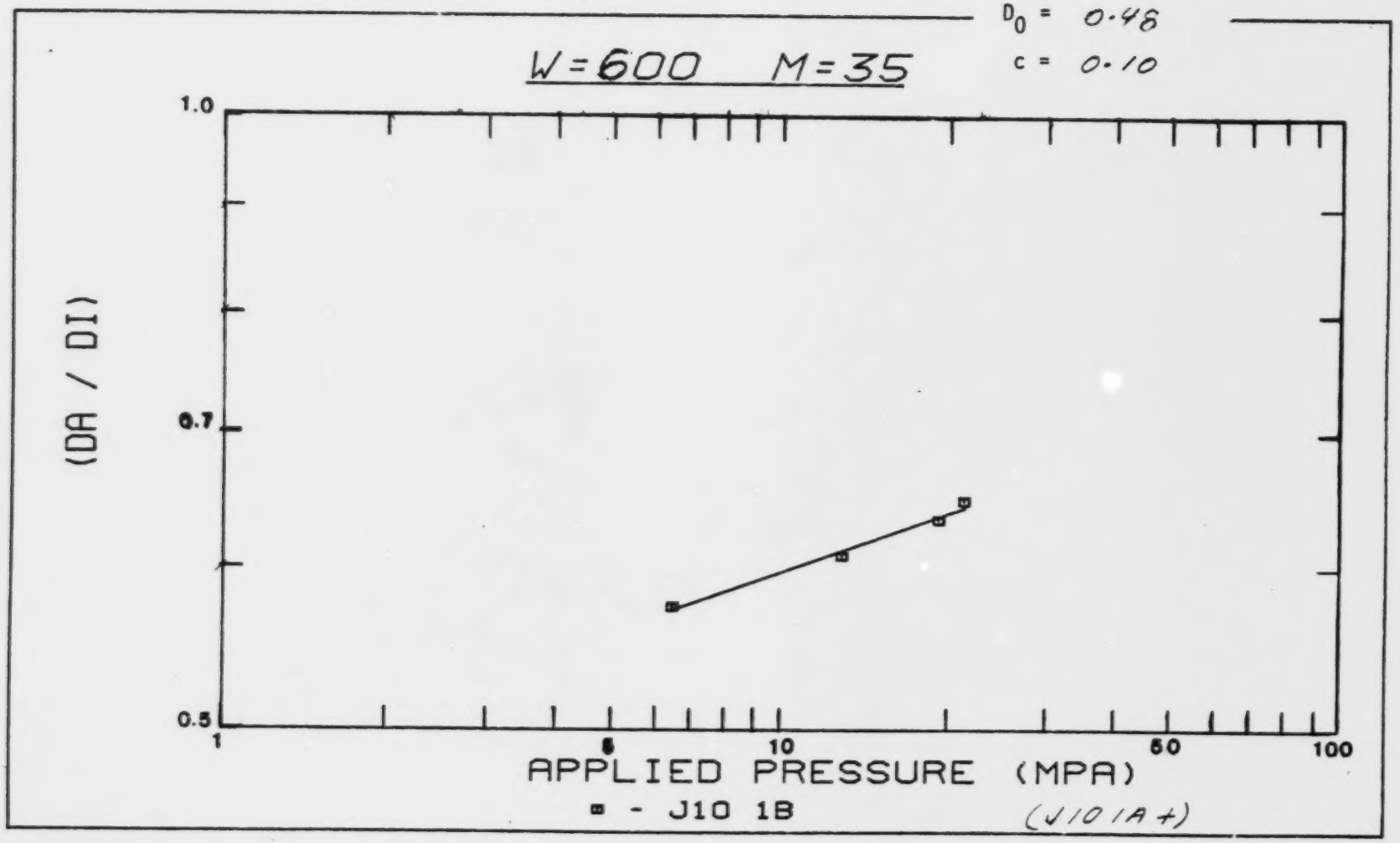
TUBE DIAMETER 880mm

PARTICLE SIZE >56·25 mm

$D_A/D_I = D_0 P^c$

$D_0 = 0.48$

$c = 0.10$



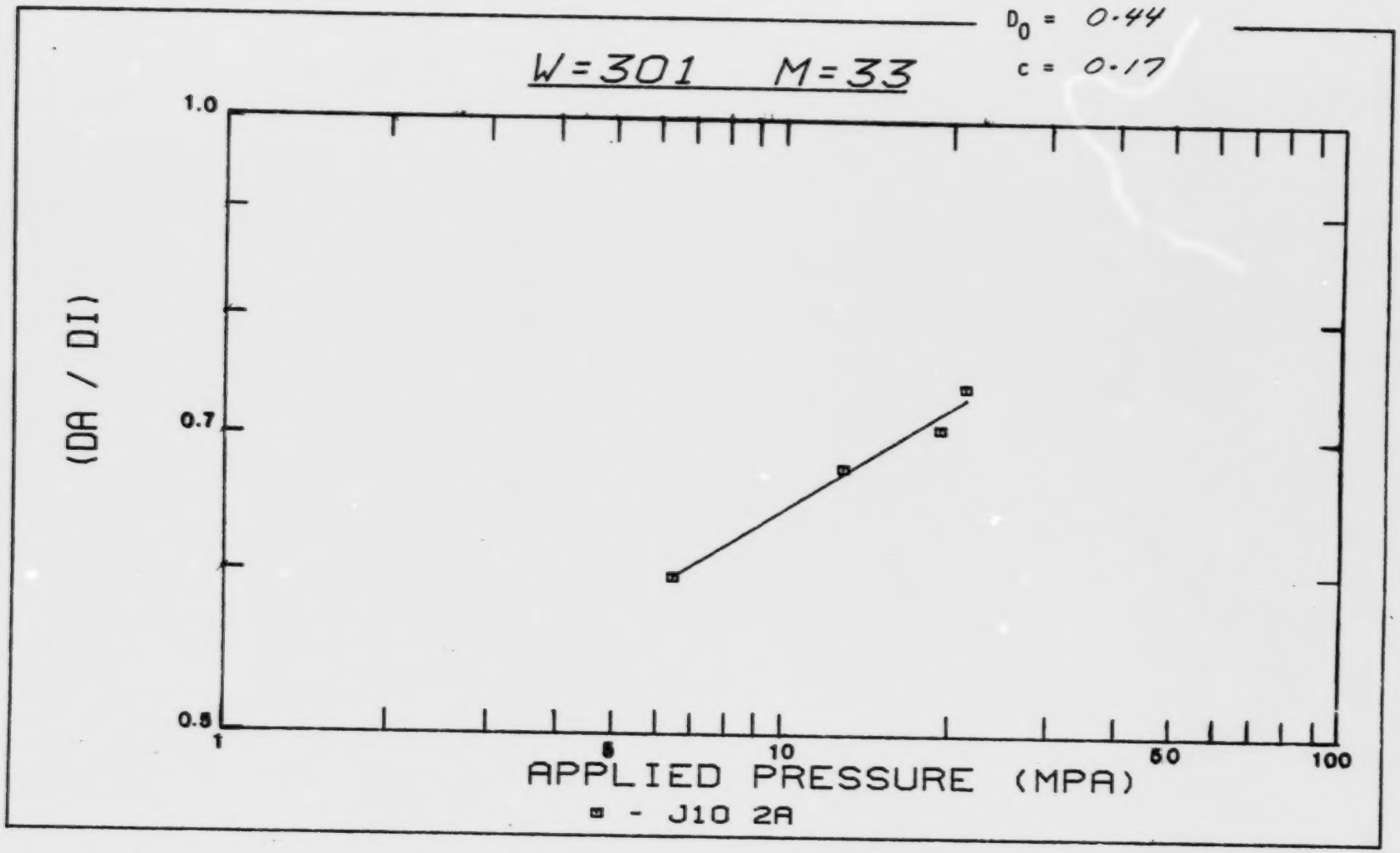
TUBE DIAMETER 880 mm

PARTICLE SIZE 56·25 - 6·35 mm

$D_A/D_I = D_0 P^c$

$D_0 = 0.44$

$c = 0.17$



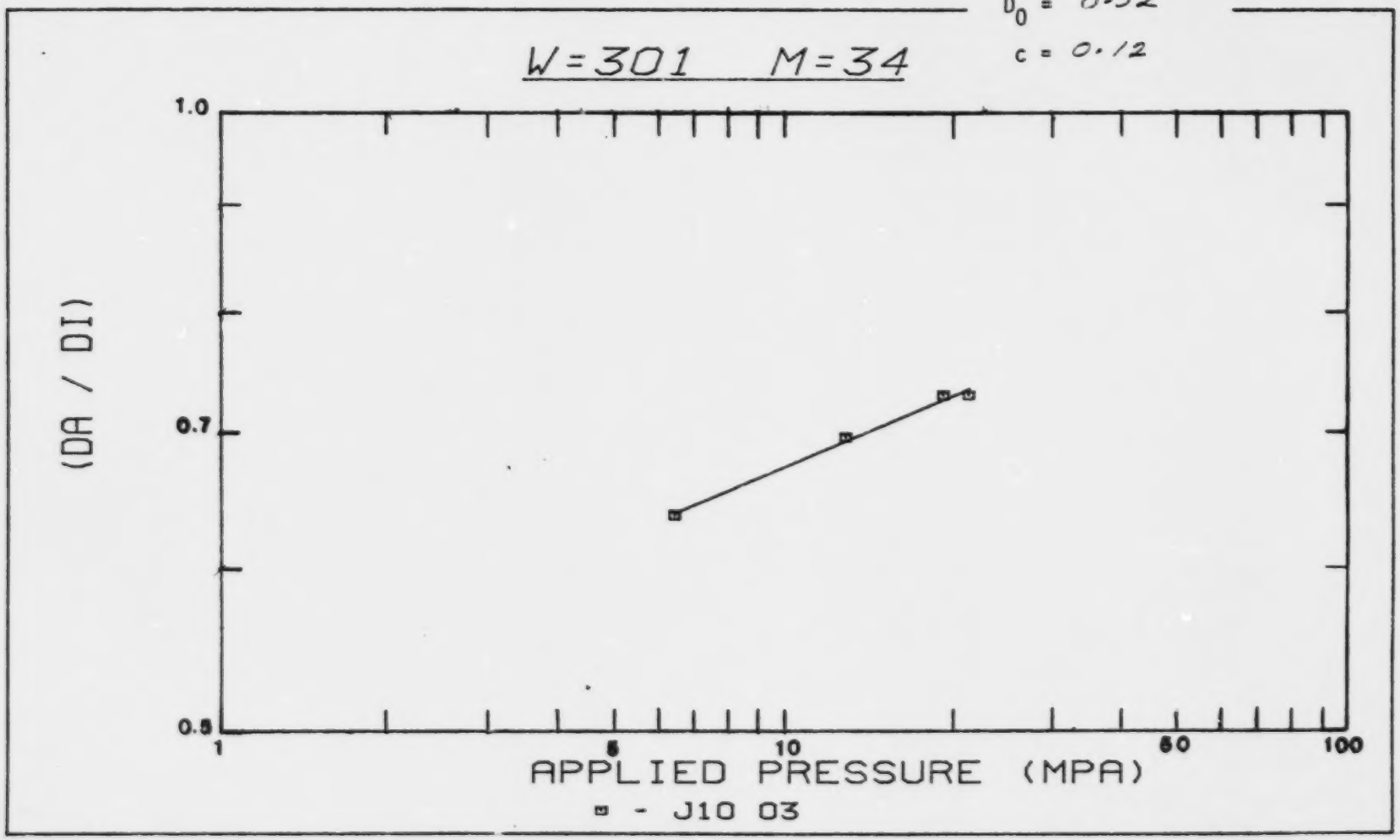
TUBE DIAMETER 880mm

PARTICLE SIZE < 6·35

$D_A/D_I = D_0 P^c$

$D_0 = 0.52$

$c = 0.12$



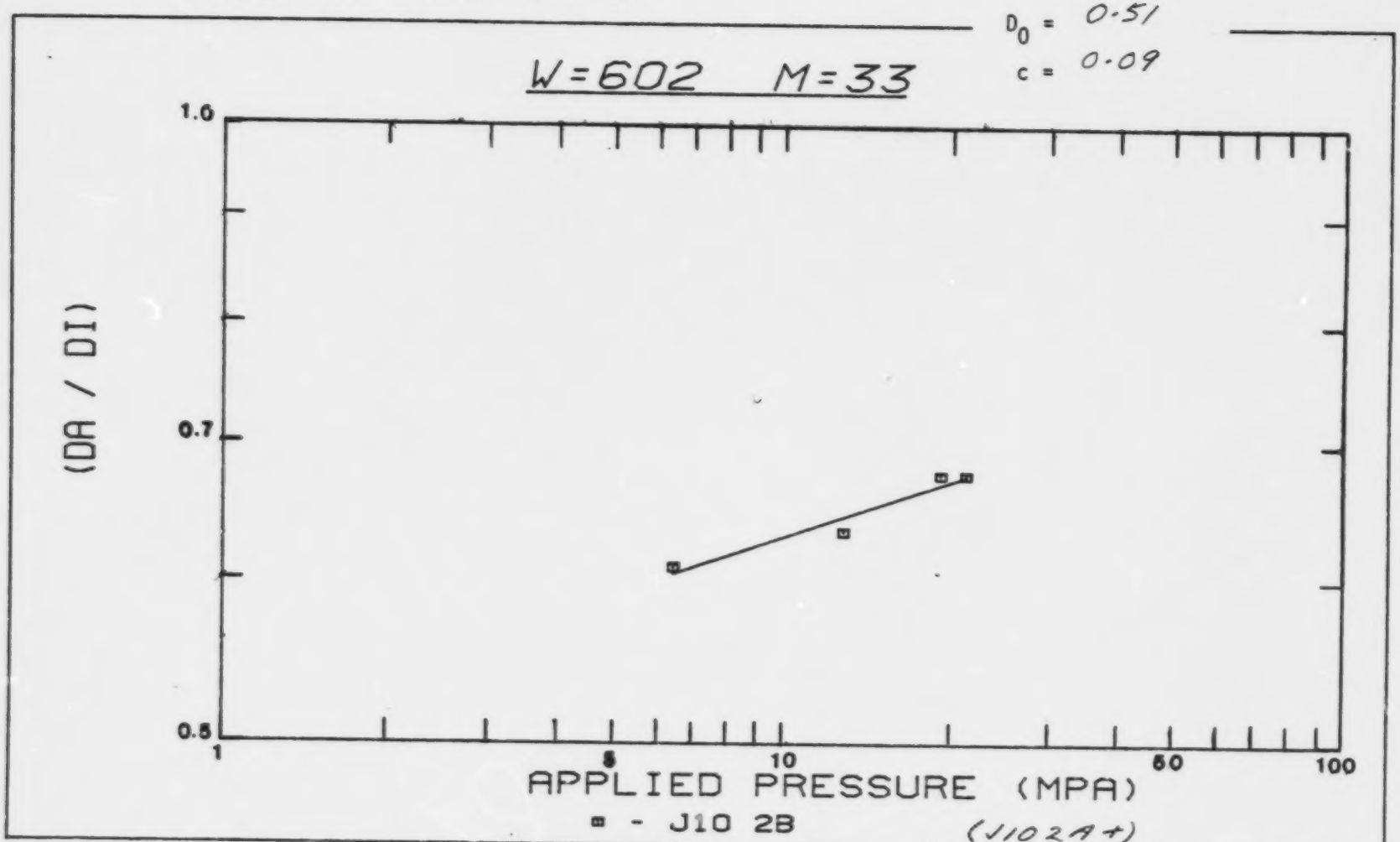
TUBE DIAMETER 880 mm

PARTICLE SIZE 56.25 - 6.35 mm

$D_A/D_I = D_0 P^C$

$D_0 = 0.51$

$c = 0.09$



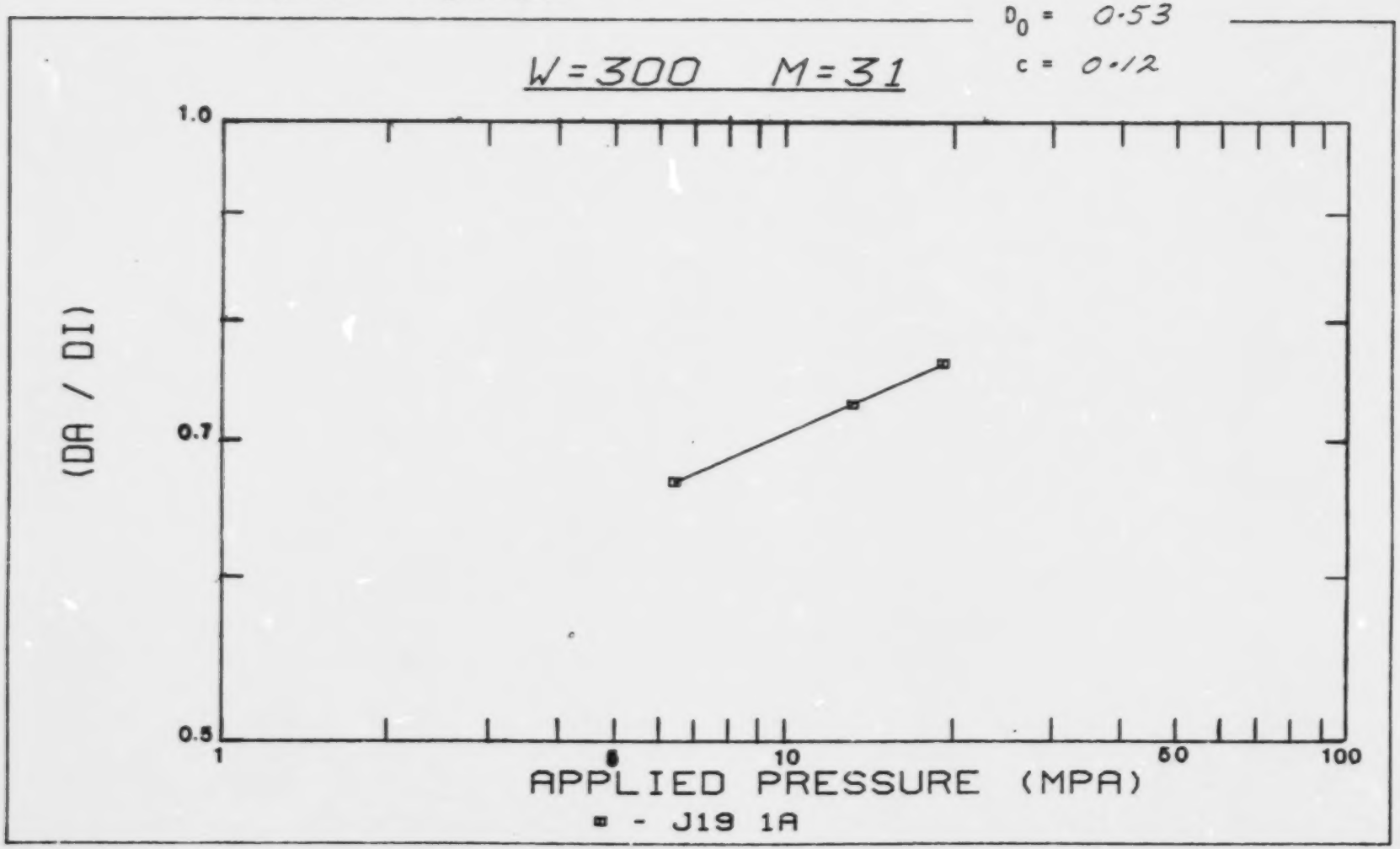
TUBE DIAMETER 880 mm

PARTICLE SIZE < 6·35 mm

$D_A/D_I = D_0 P^c$

$D_0 = 0.53$

$c = 0.12$



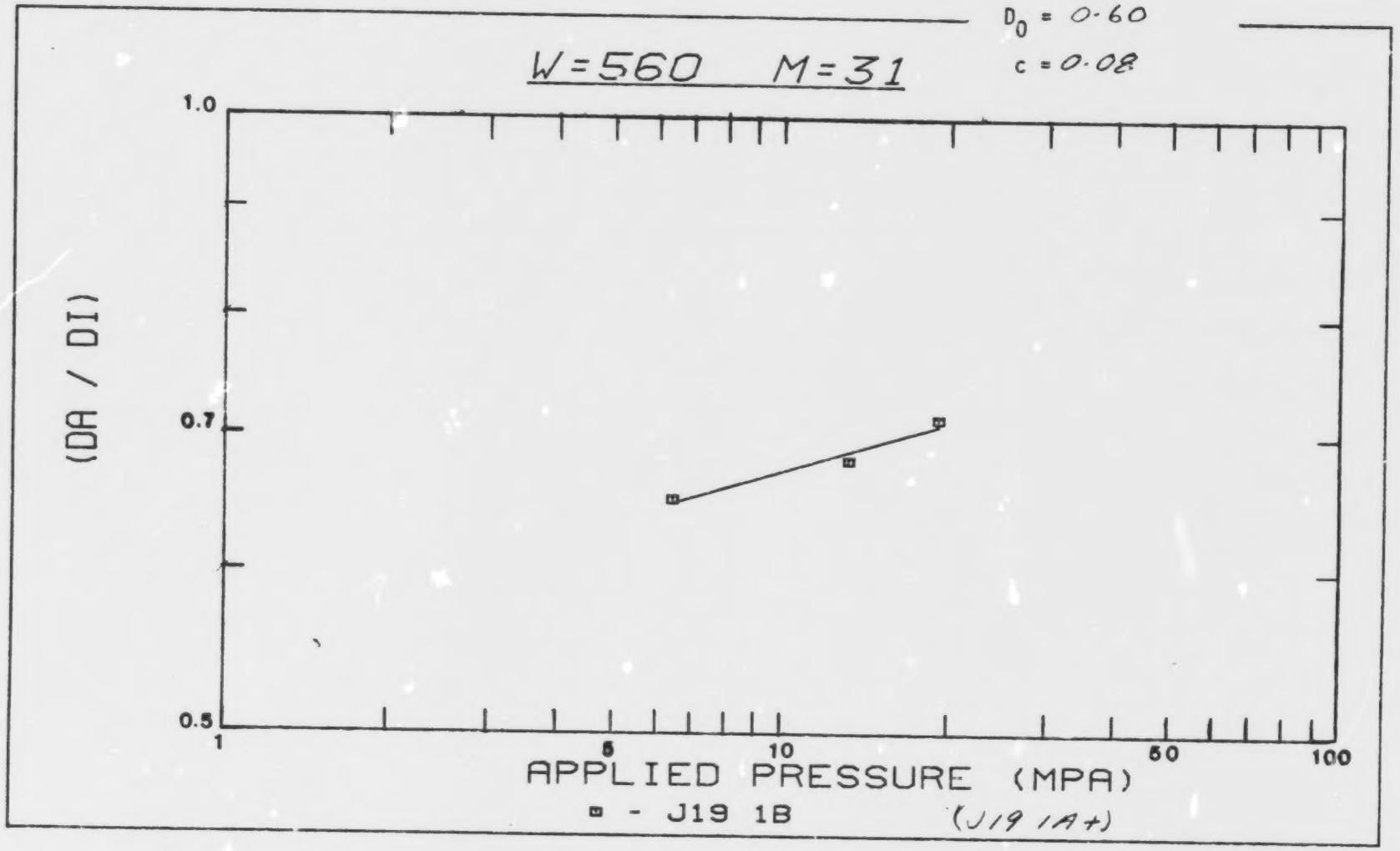
TUBE DIAMETER 880mm

PARTICLE SIZE < 6.35 mm

$D_A/D_I = D_0 P^C$

$D_0 = 0.60$

$c = 0.08$



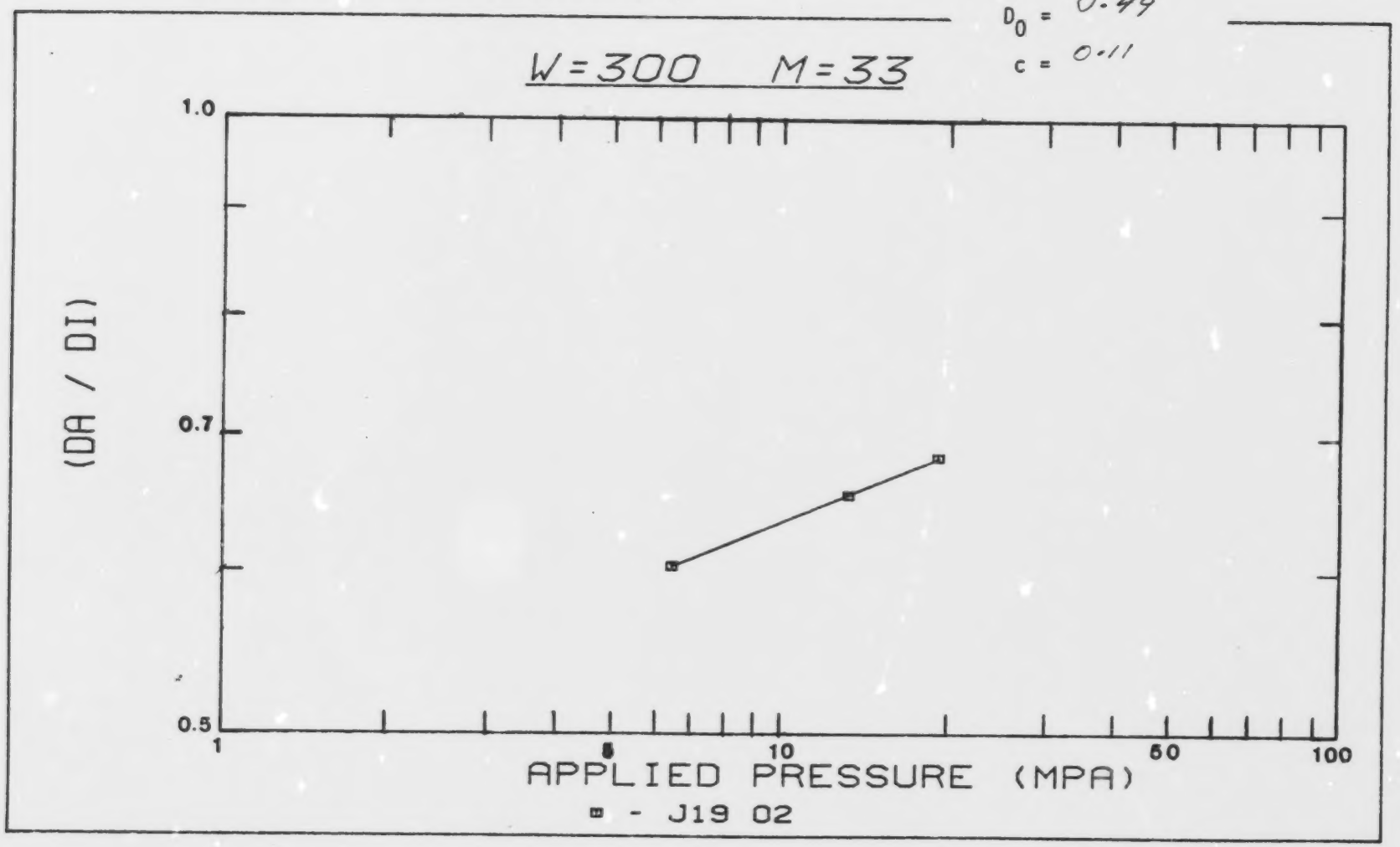
TUBE DIAMETER 880 mm

PARTICLE SIZE 56.25 - 4.76 mm

$D_A/D_I = D_0 P^c$

$D_0 = 0.49$

$c = 0.11$



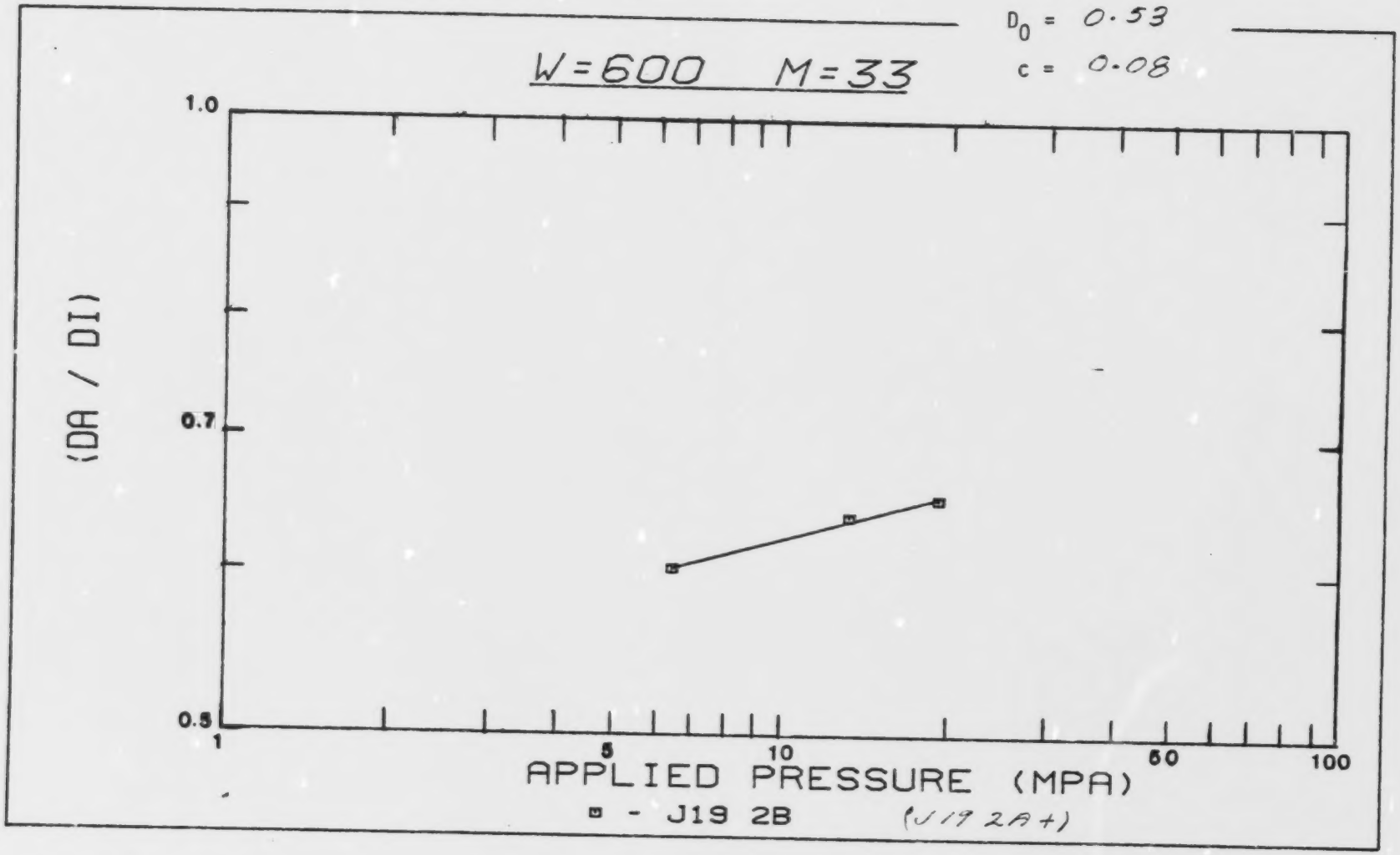
TUBE DIAMETER 880 mm

PARTICLE SIZE 56·25 – 4·76 mm

$D_A/D_I = D_0 P^c$

$D_0 = 0.53$

$c = 0.08$



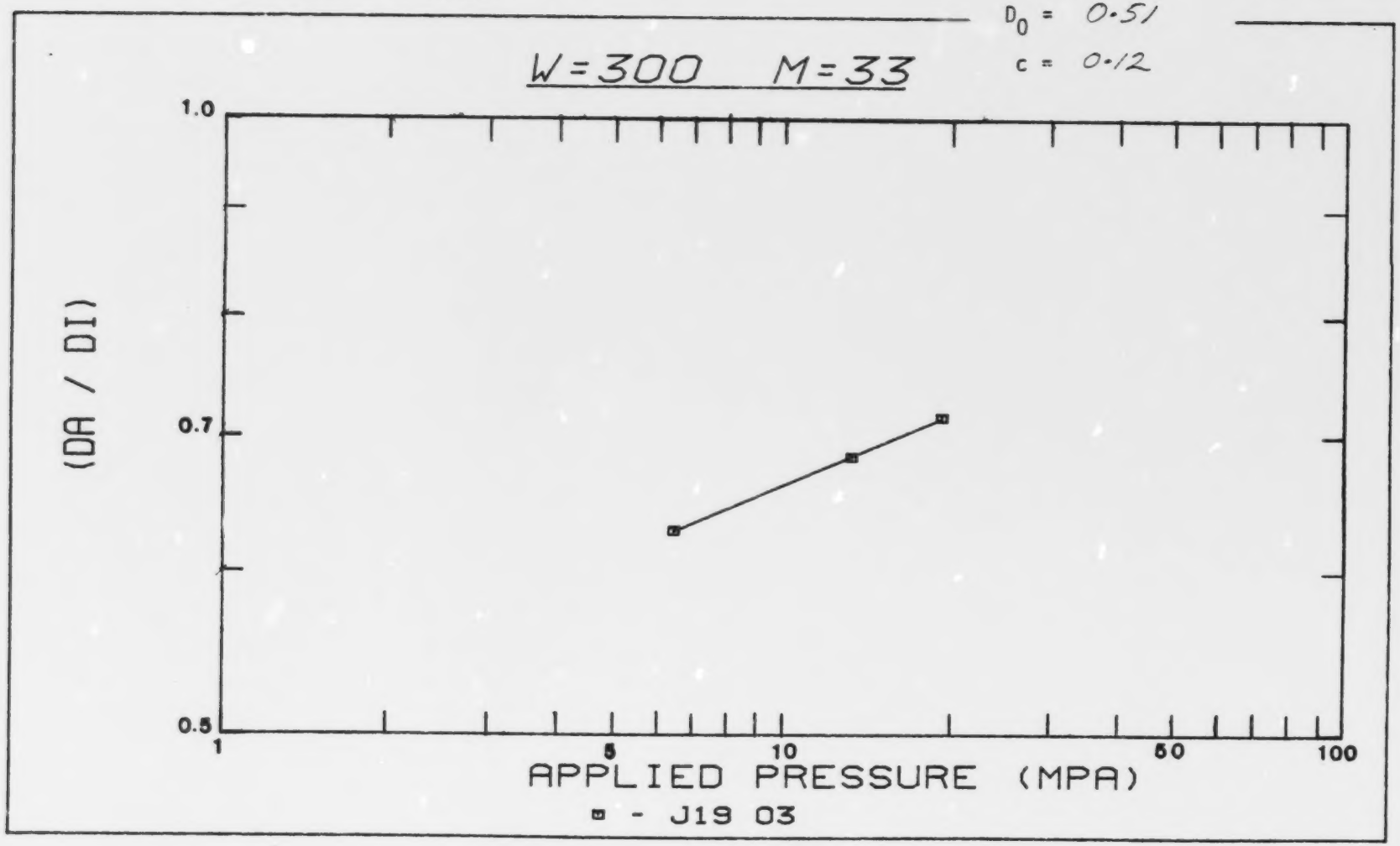
TUBE DIAMETER 880mm

PARTICLE SIZE MIXED

$D_A/D_I = D_0 P^c$

$D_0 = 0.51$

$c = 0.12$



TUBE DIAMETER 500 mm

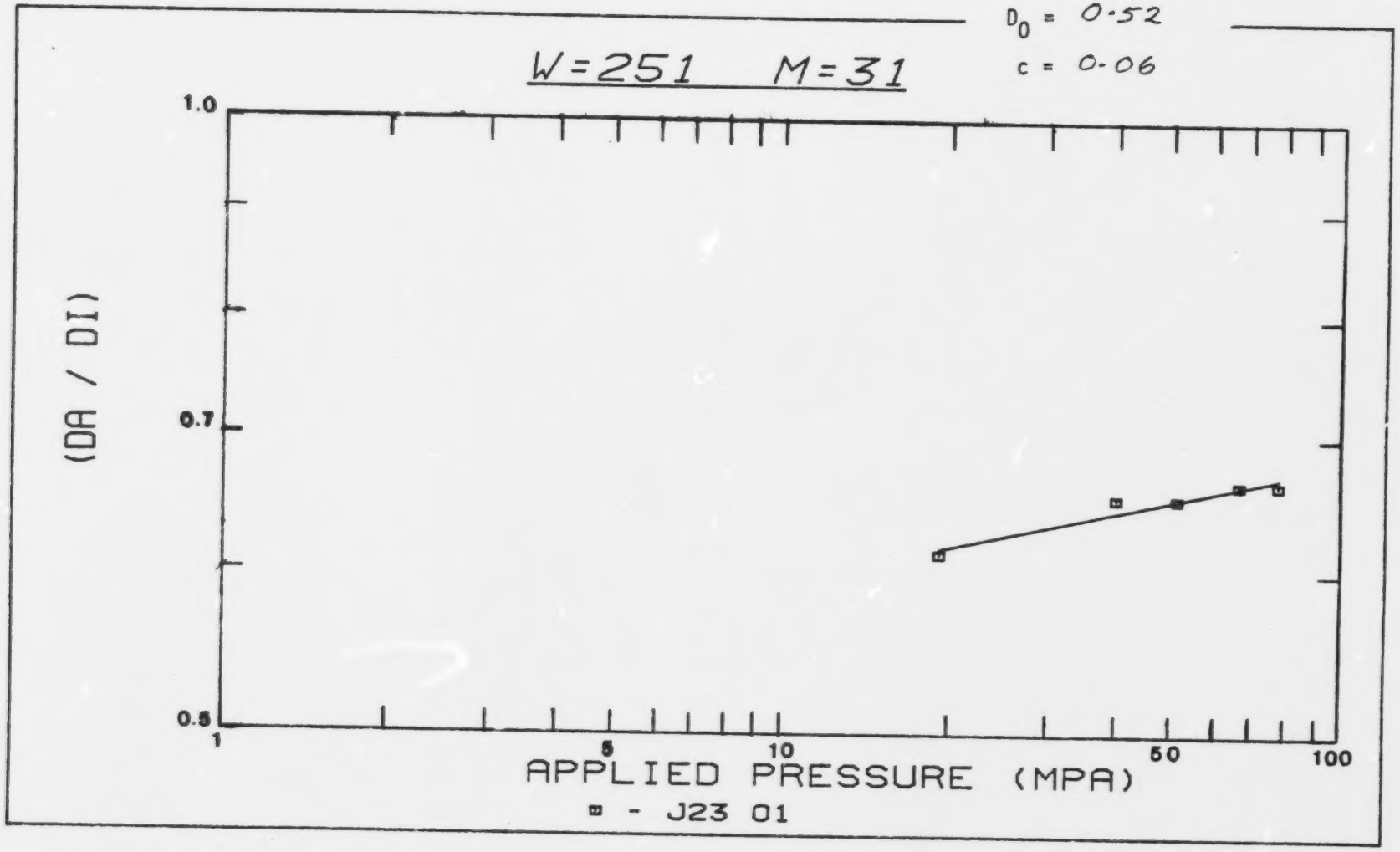
PARTICLE SIZE < 4.76

$D_A/D_I = D_0 P^c$

$D_0 = 0.52$

$c = 0.06$

W=251 M=31



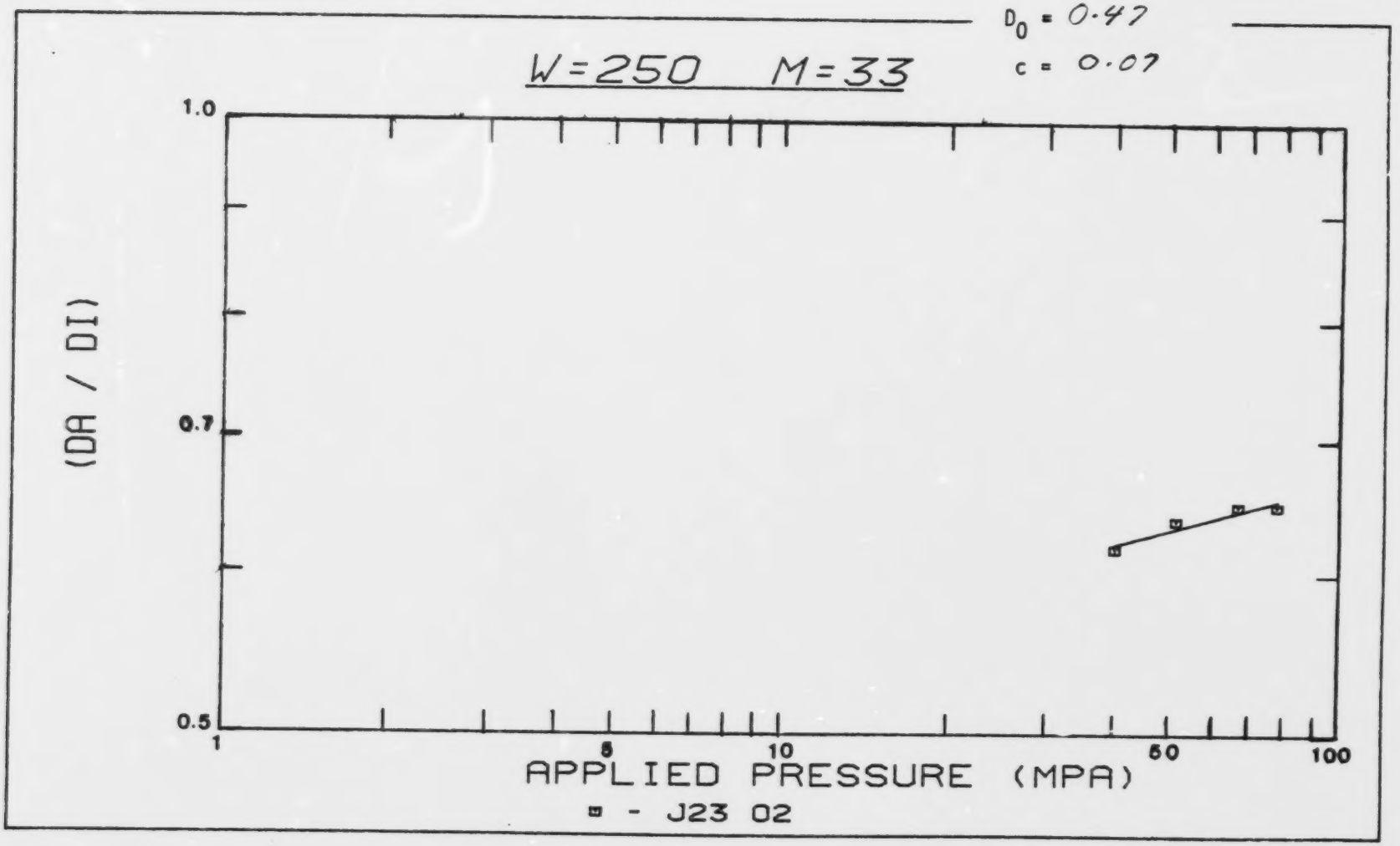
TUBE DIAMETER 500 m

PARTICLE SIZE 56.25 - 4.76 mm

$D_A/D_I = D_0 P^C$

$D_0 = 0.47$

$c = 0.07$



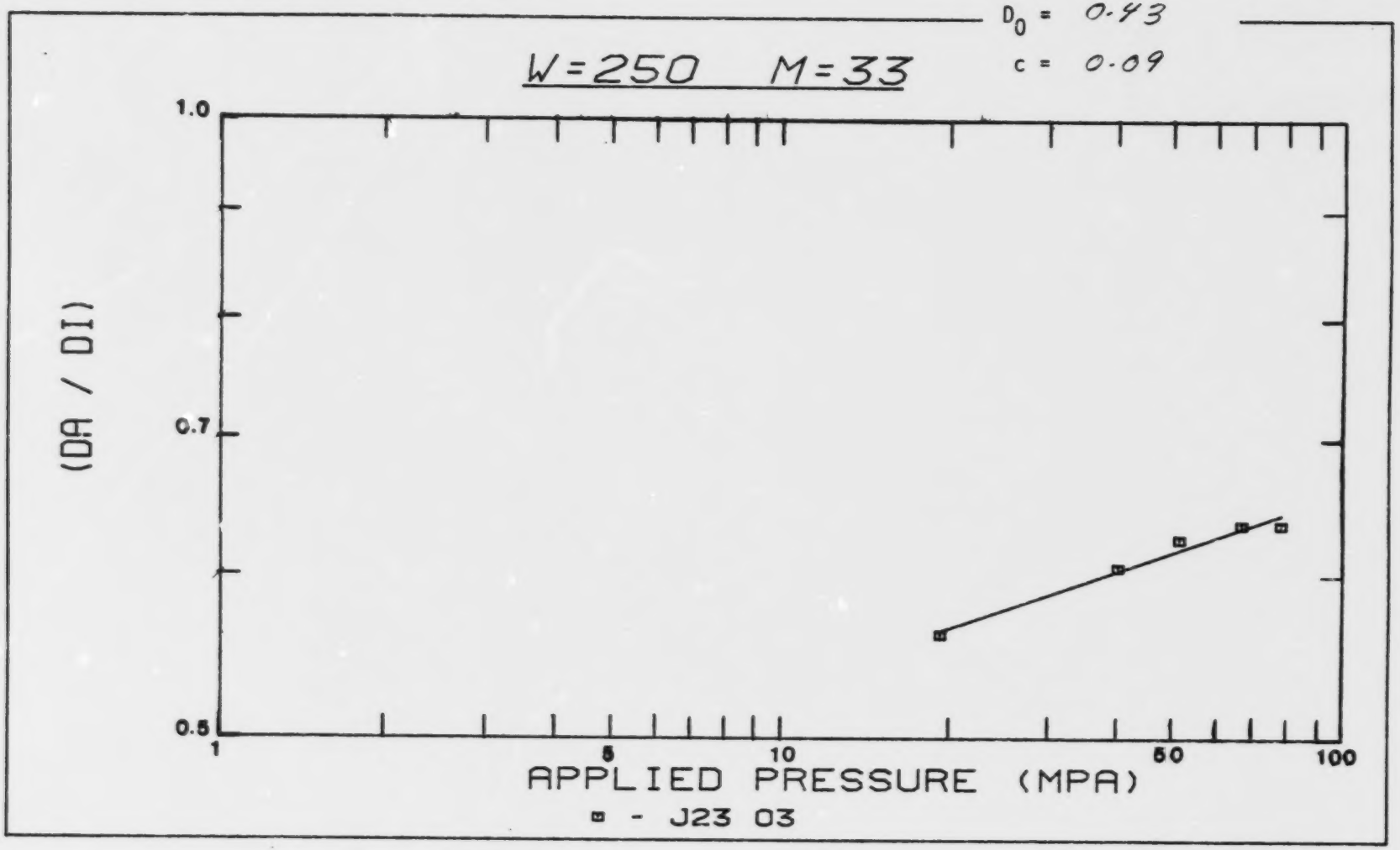
TUBE DIAMETER 500mm

PARTICLE SIZE >56·25

$D_A/D_I = D_0 P^C$

$D_0 = 0.43$

$c = 0.09$



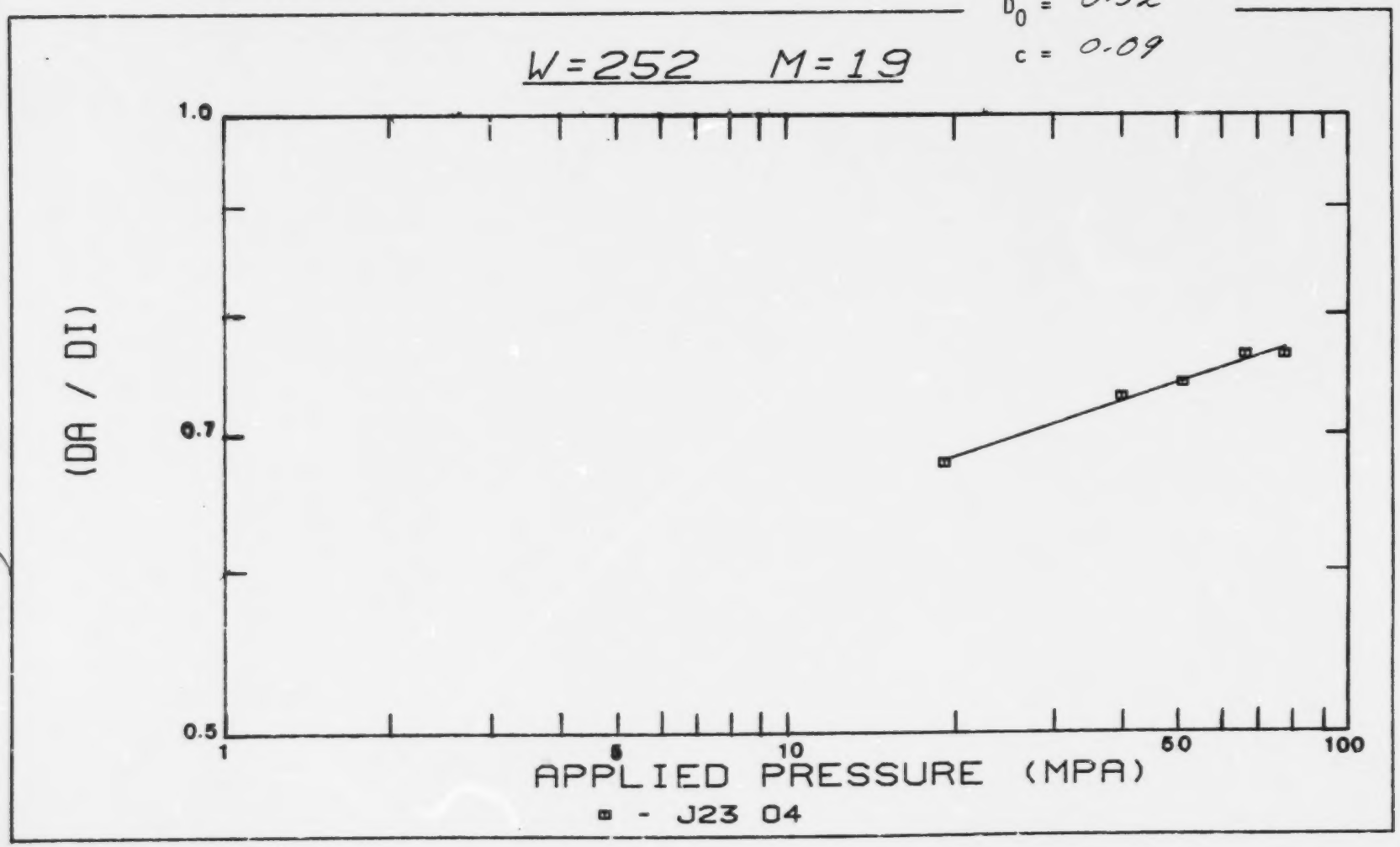
TUBE DIAMETER 500mm

PARTICLE SIZE >56.25

$D_A/D_I = D_0 P^c$

$D_0 = 0.52$

$c = 0.09$



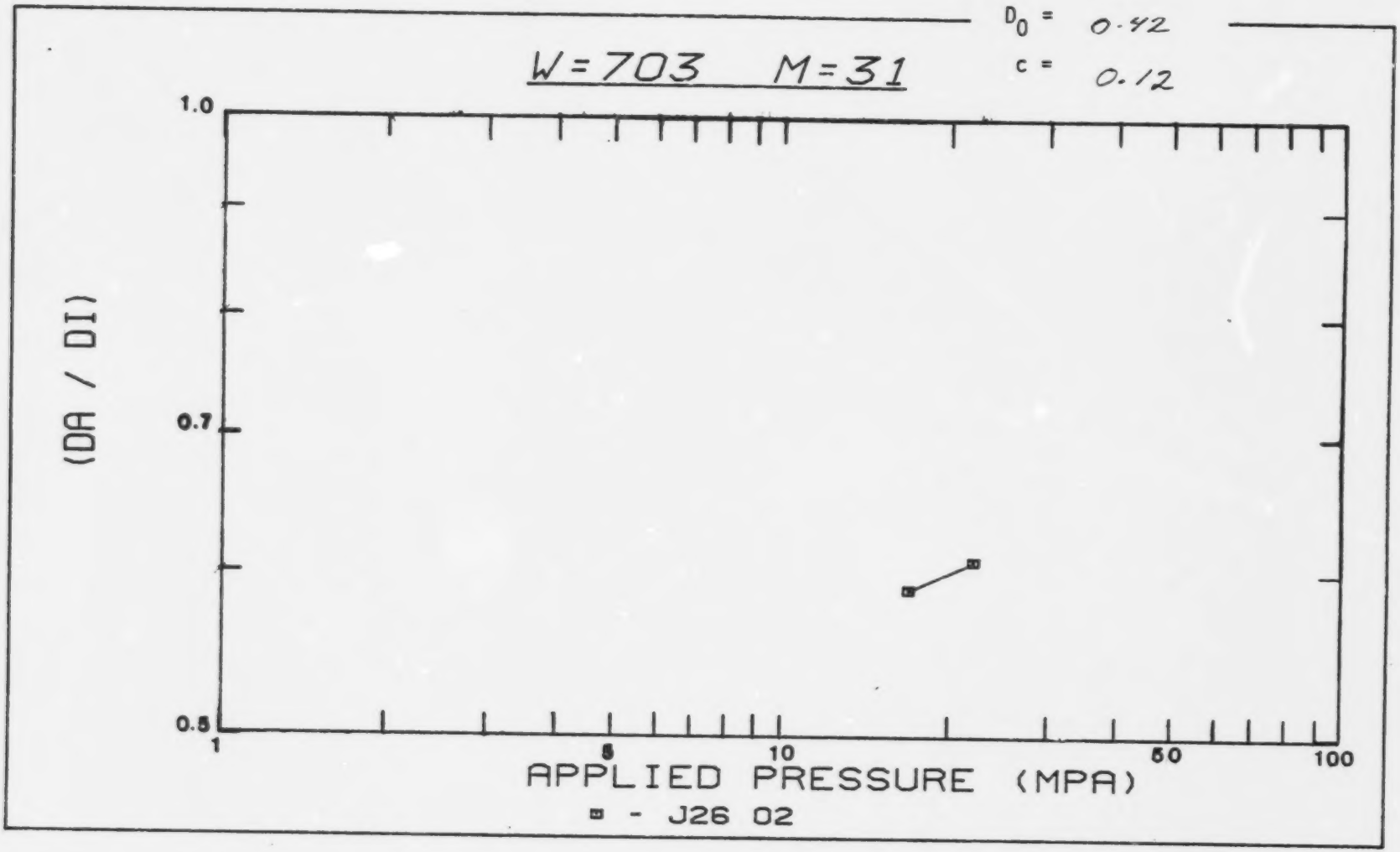
TUBE DIAMETER 500 mm

PARTICLE SIZE AS RECEIVED

$D_A/D_I = D_0 P^c$

D_0 = 0.42

c = 0.12



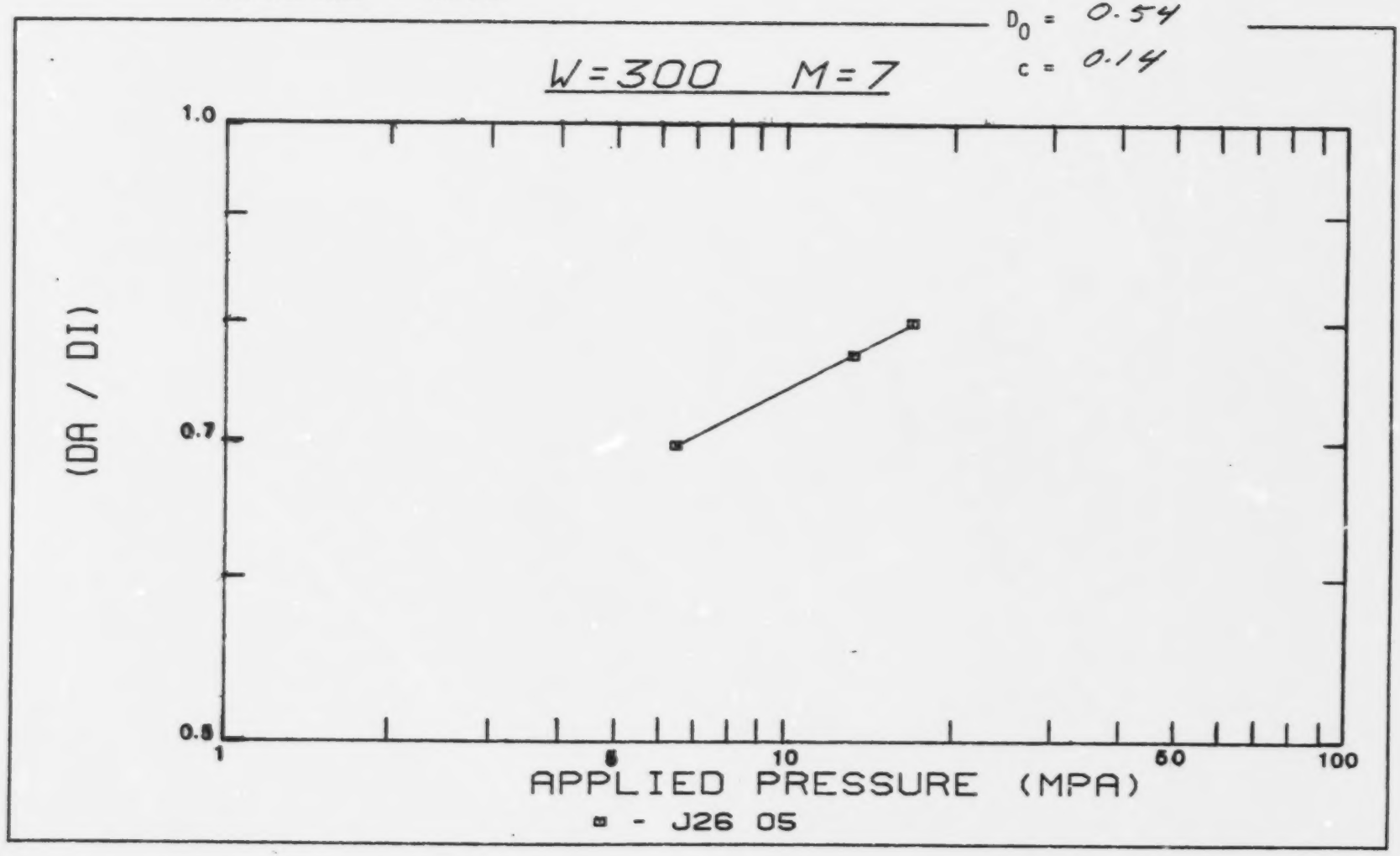
TUBE DIAMETER 500mm

PARTICLE SIZE < 4.76

$D_A/D_I = D_0 P^C$

$D_0 = 0.54$

$c = 0.14$



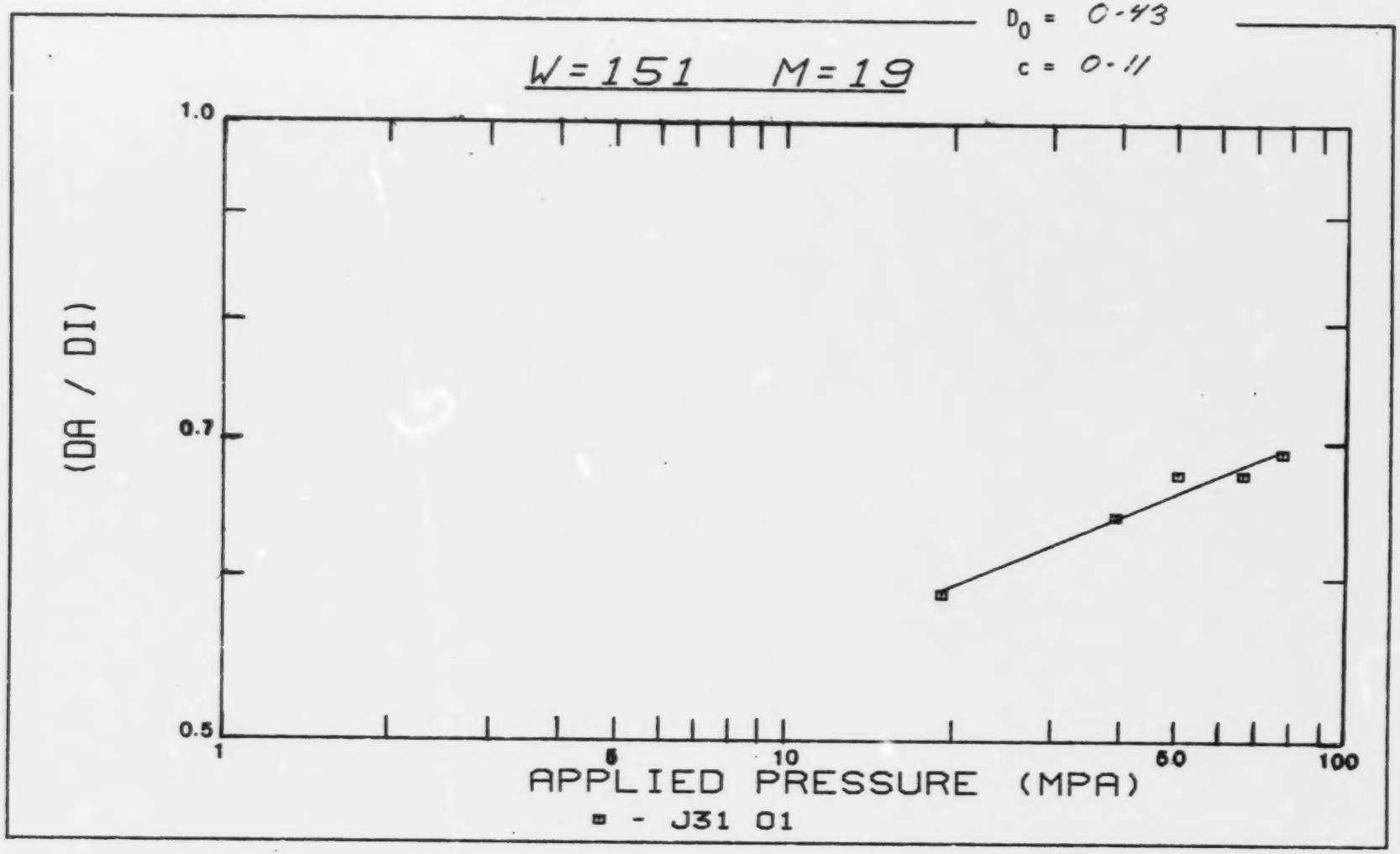
TUBE DIAMETER 500 mm

PARTICLE SIZE > 56.25 mm

$D_A/D_I = D_0 P^c$

$D_0 = 0.43$

$c = 0.11$



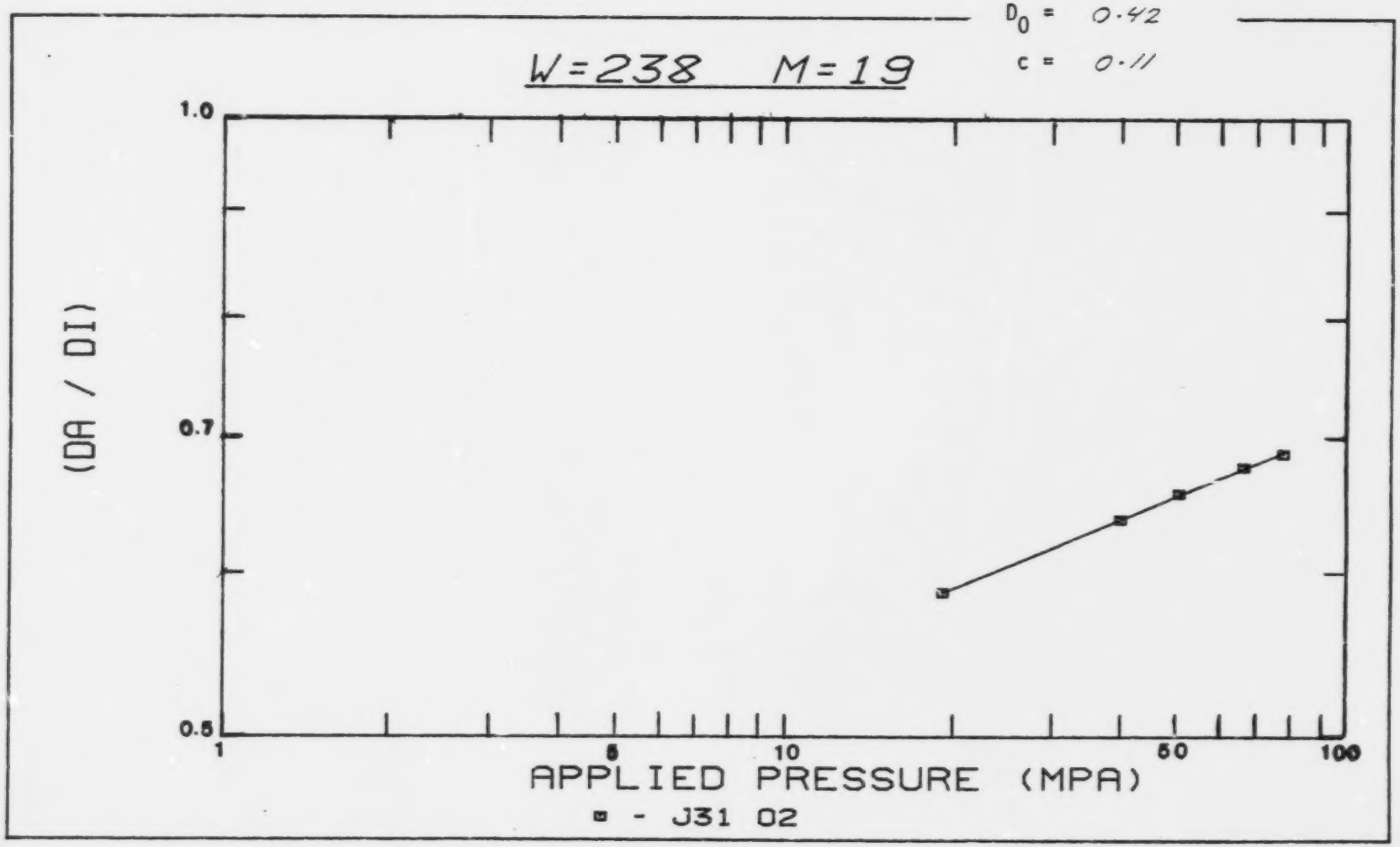
TUBE DIAMETER 500 mm

PARTICLE SIZE > 56·25 mm

$D_A/D_I = D_0 P^c$

$D_0 = 0.42$

$c = 0.11$



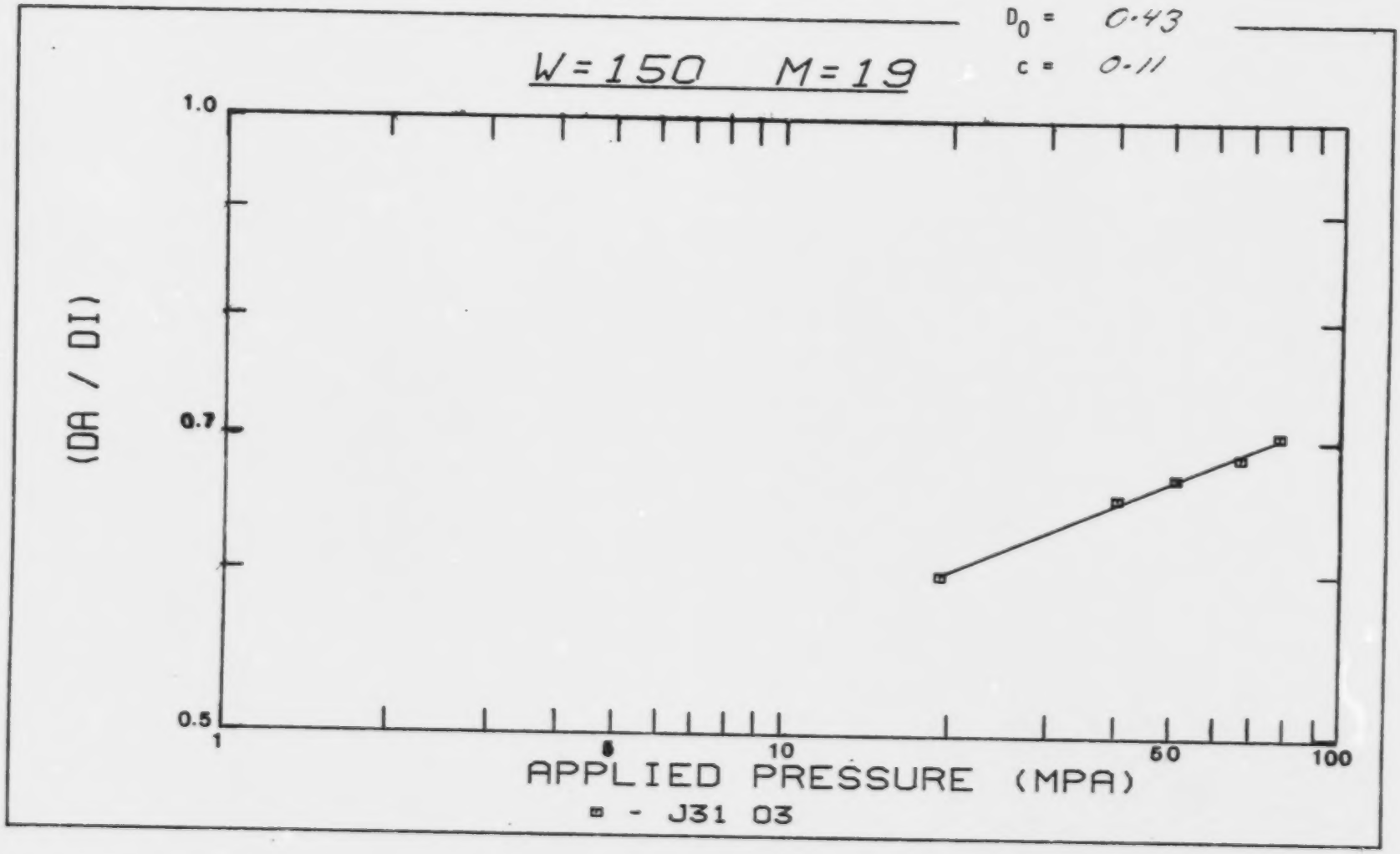
TUBE DIAMETER 500mm

PARTICLE SIZE 56·25 - 4·76 mm

$D_A/D_I = D_0 P^c$

$D_0 =$ 0·43

$c =$ 0·11



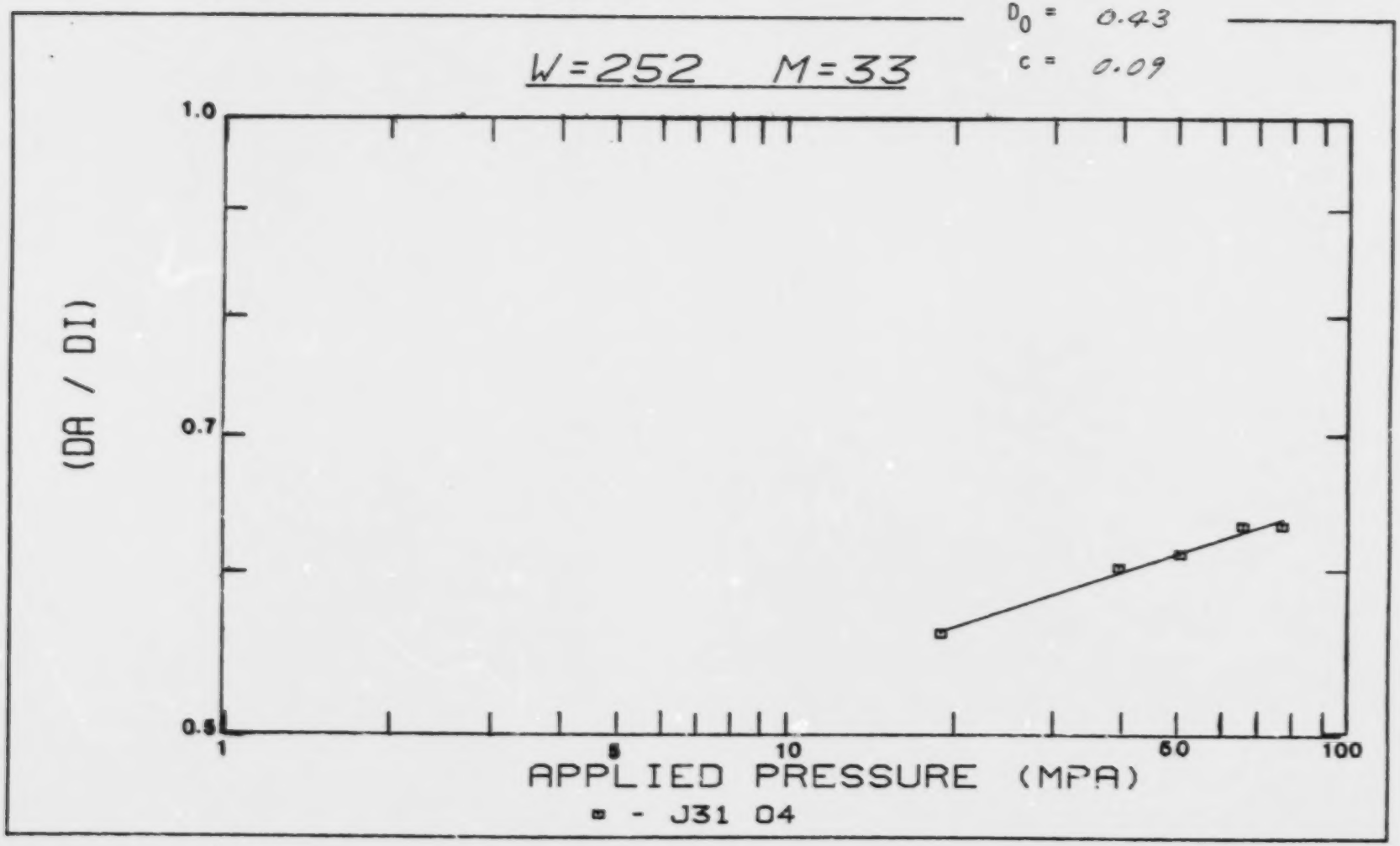
TUBE DIAMETER 500 mm

PARTICLE SIZE 56.25 - 4.76 mm

$D_A/D_I = D_0 P^c$

$D_0 =$ 0.43

$c =$ 0.09



TUBE DIAMETER 500 mm

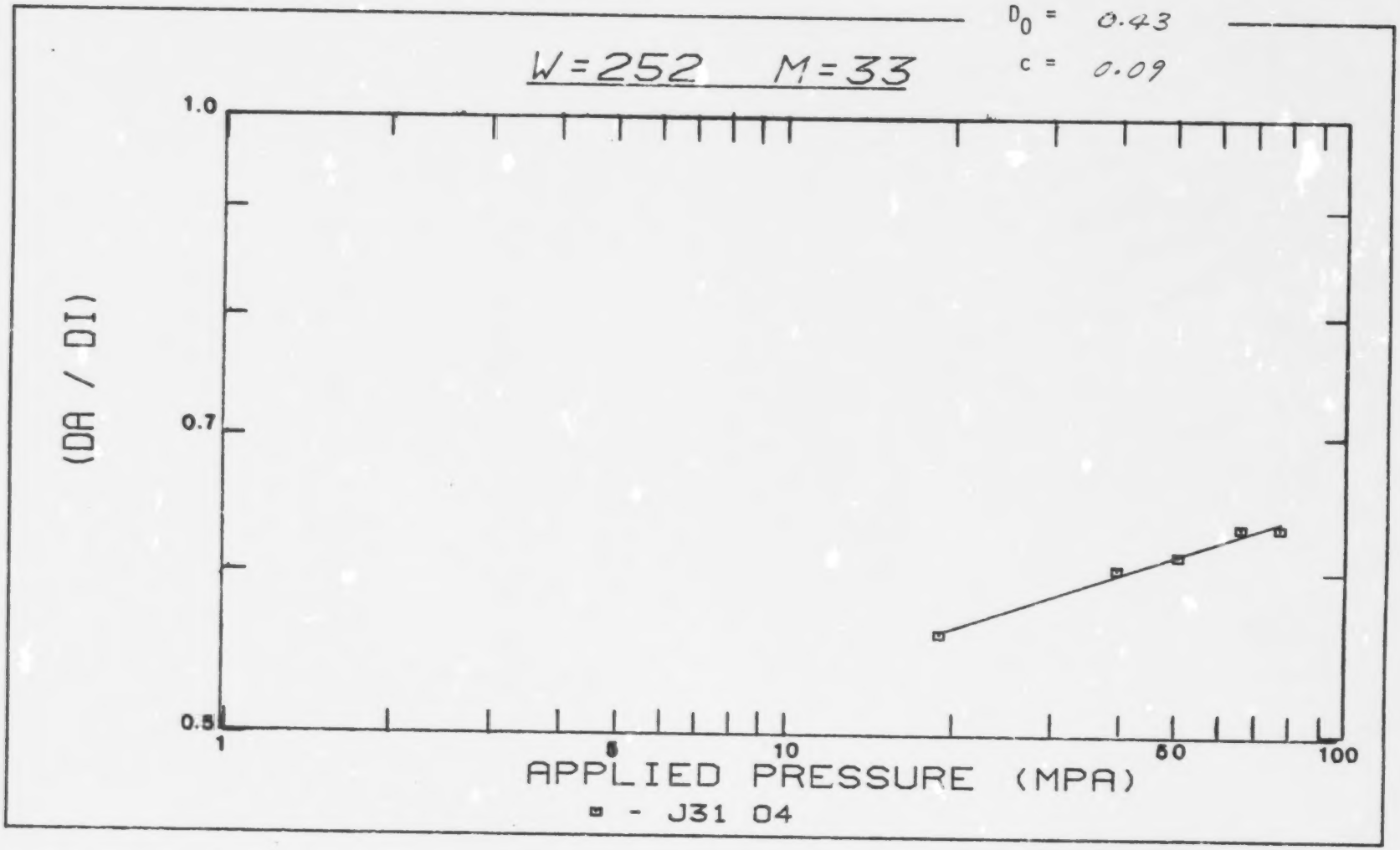
PARTICLE SIZE 56.25 - 4.76 mm

$D_A/D_I = D_0 P^C$

$D_0 =$ 0.43

$c =$ 0.09

W=252 M=33



TUBE DIAMETER 500 mm

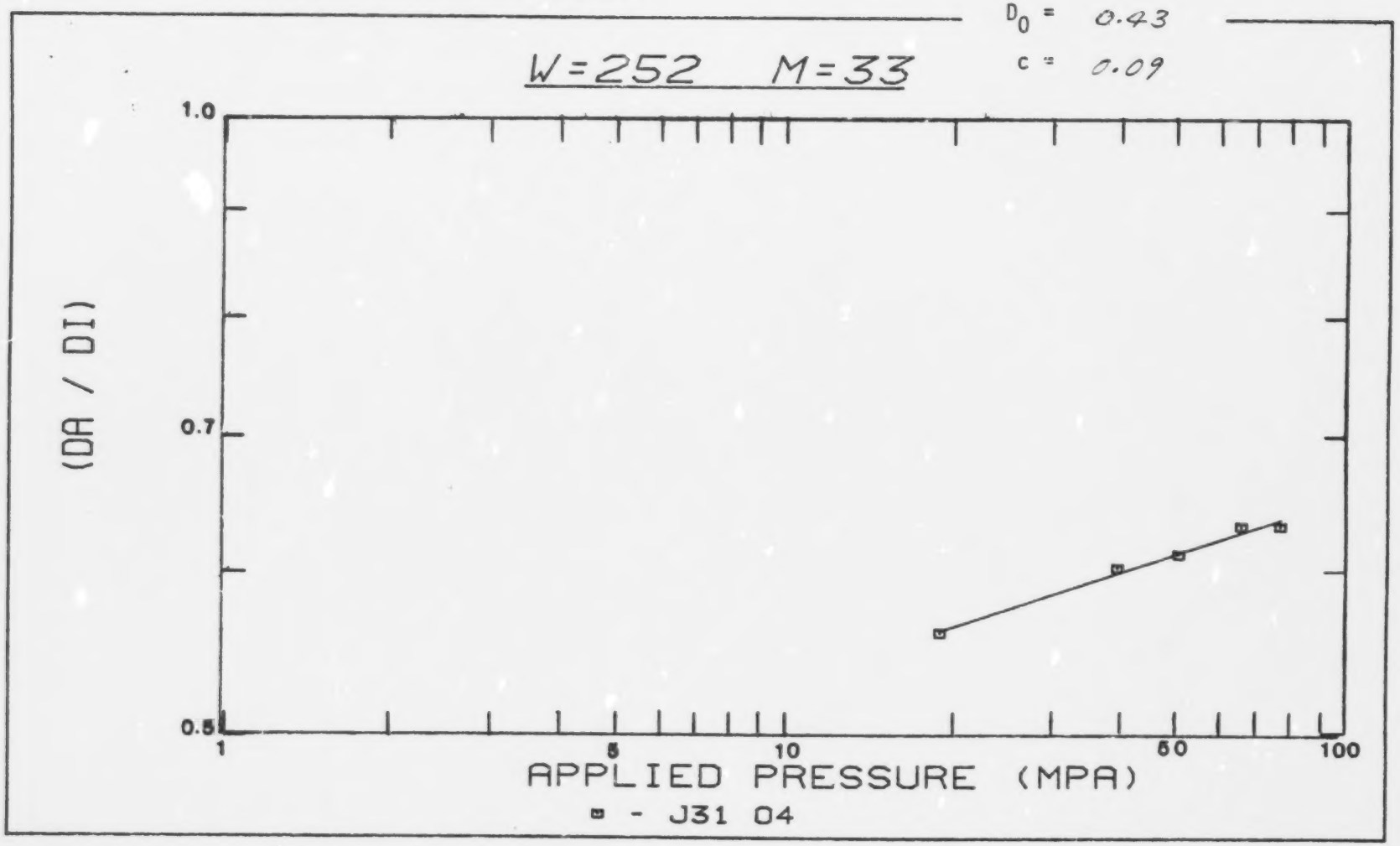
PARTICLE SIZE 56.25 - 4.76 mm

$D_A/D_I = D_0 P^c$

$D_0 =$ 0.43

$c =$ 0.09

W=252 M=33



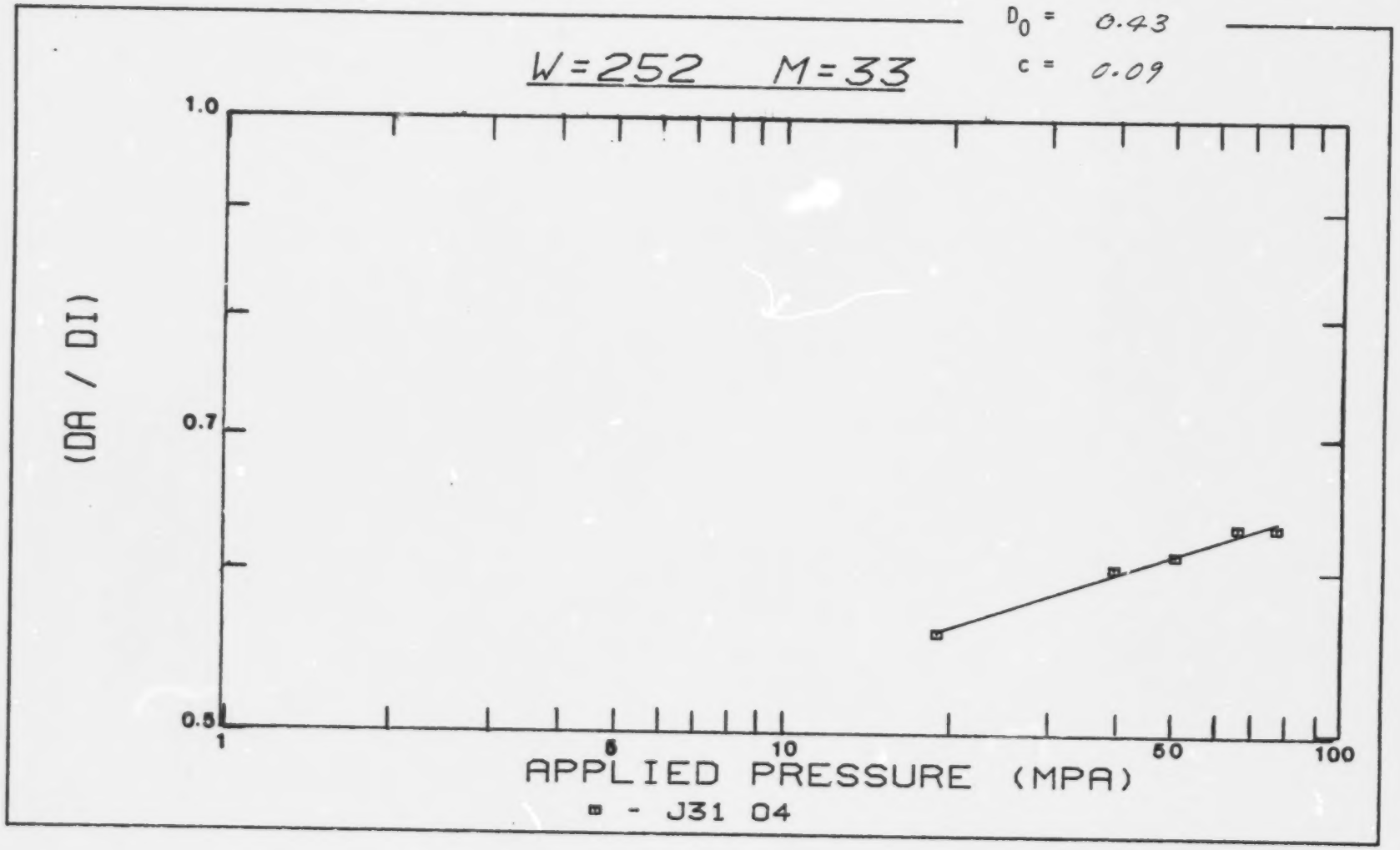
TUBE DIAMETER 500 mm

PARTICLE SIZE 56.25 - 4.76 mm

$D_A/D_I = D_0 P^C$

$D_0 =$ 0.43

$c =$ 0.09



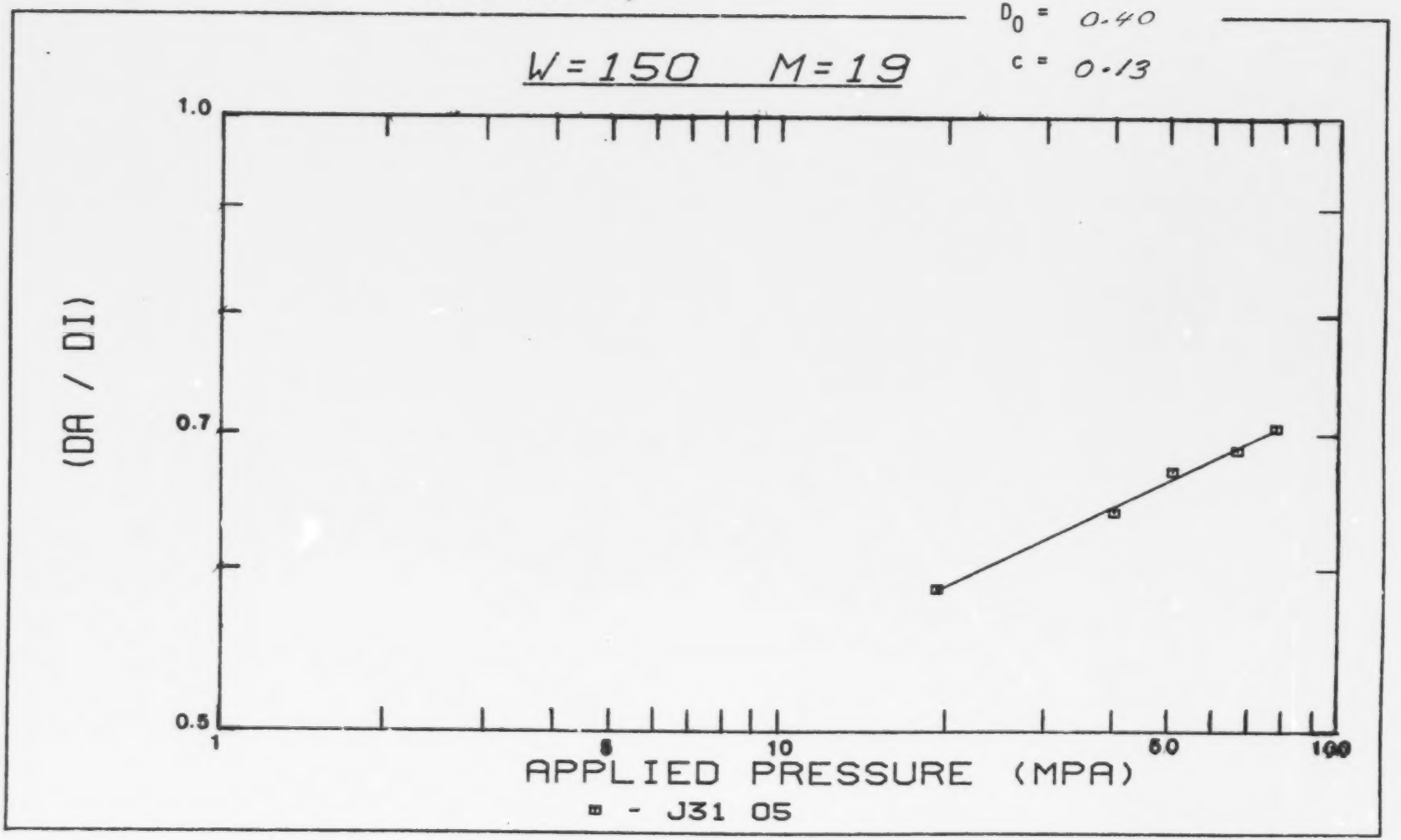
TUBE DIAMETER 500 mm

PARTICLE SIZE 4.76 - 3.17 mm

$D_A/D_I = D_0 P^c$

$D_0 = 0.40$

$c = 0.13$



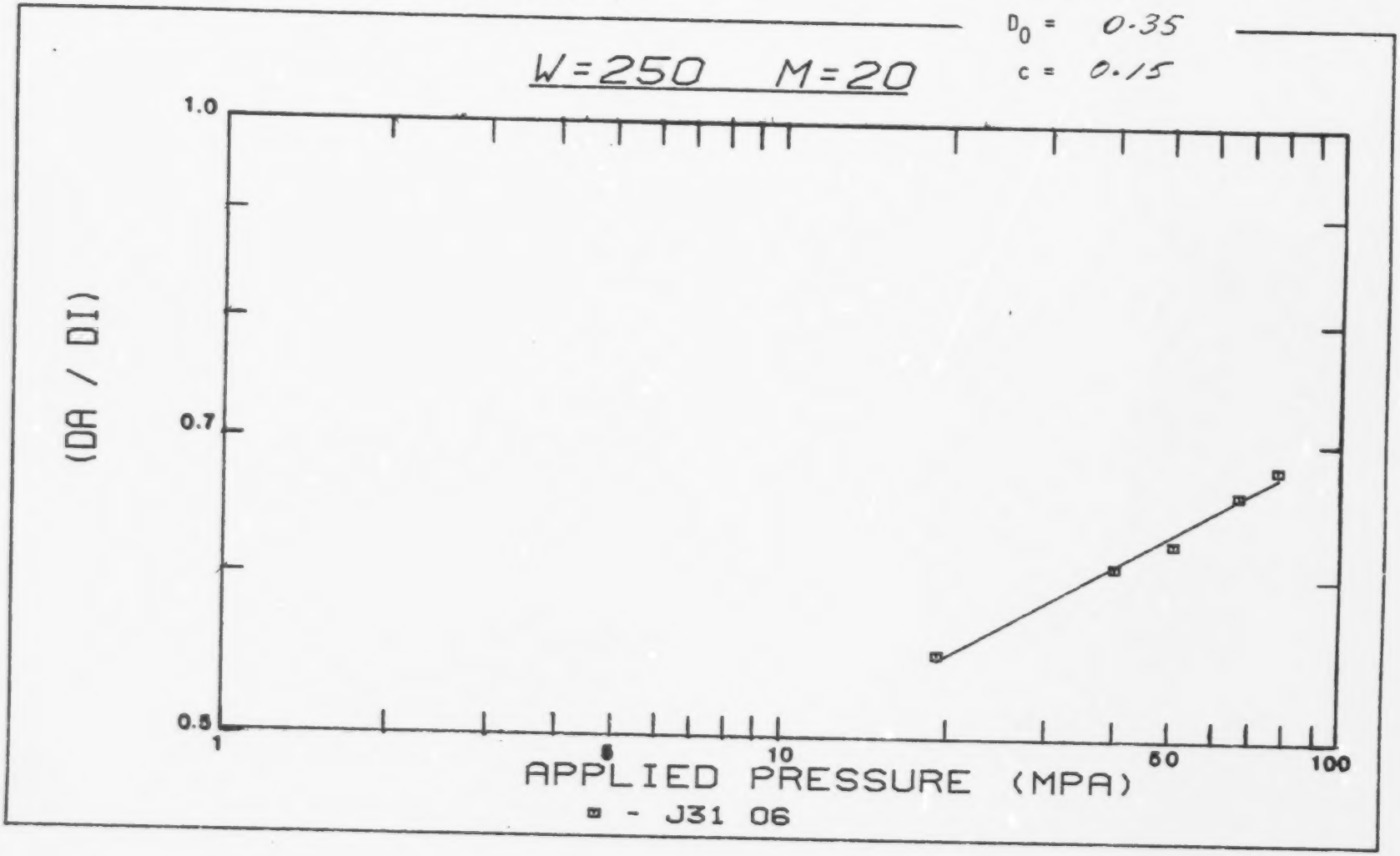
TUBE DIAMETER 500mm

PARTICLE SIZE 4.76 – 3.17mm

$D_A/D_I = D_0 P^c$

$D_0 = 0.35$

$c = 0.15$



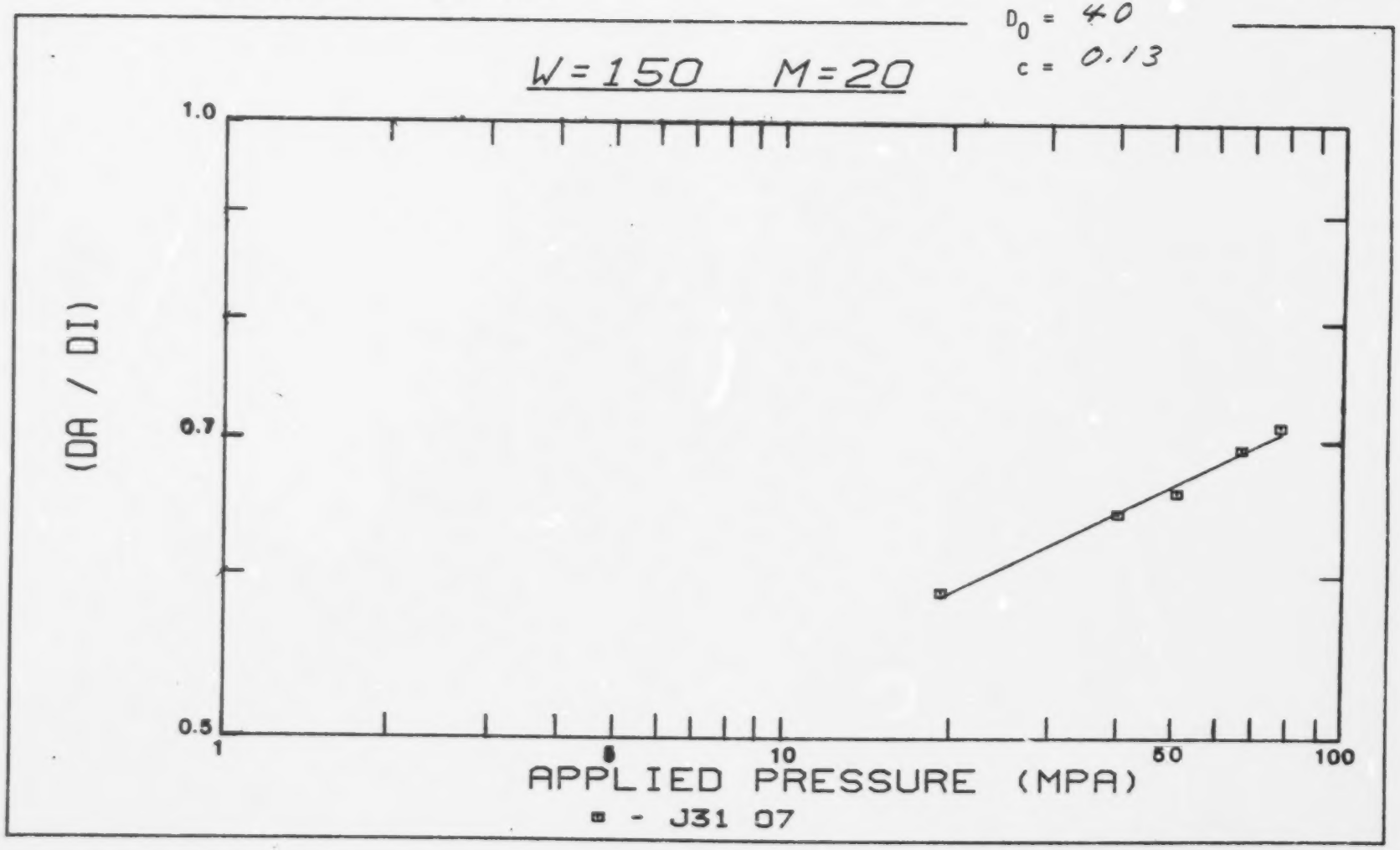
TUBE DIAMETER 500 mm

PARTICLE SIZE < 3.17 mm

$D_A/D_I = D_0 P^c$

$D_0 = 40$

$c = 0.13$



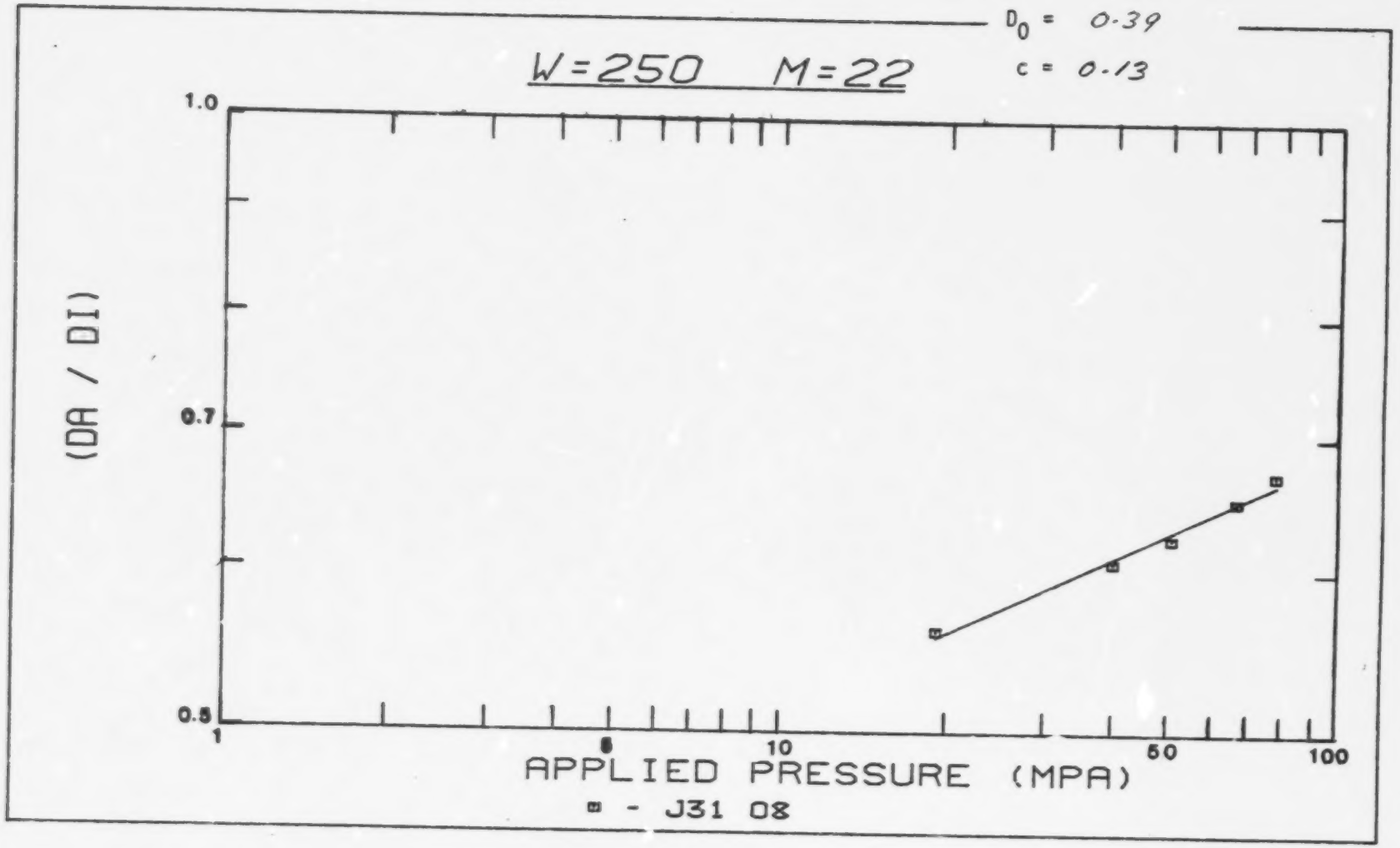
TUBE DIAMETER 500 mm

PARTICLE SIZE < 3.17 mm

$D_A/D_I = D_0 P^c$

$D_0 = 0.39$

$c = 0.13$



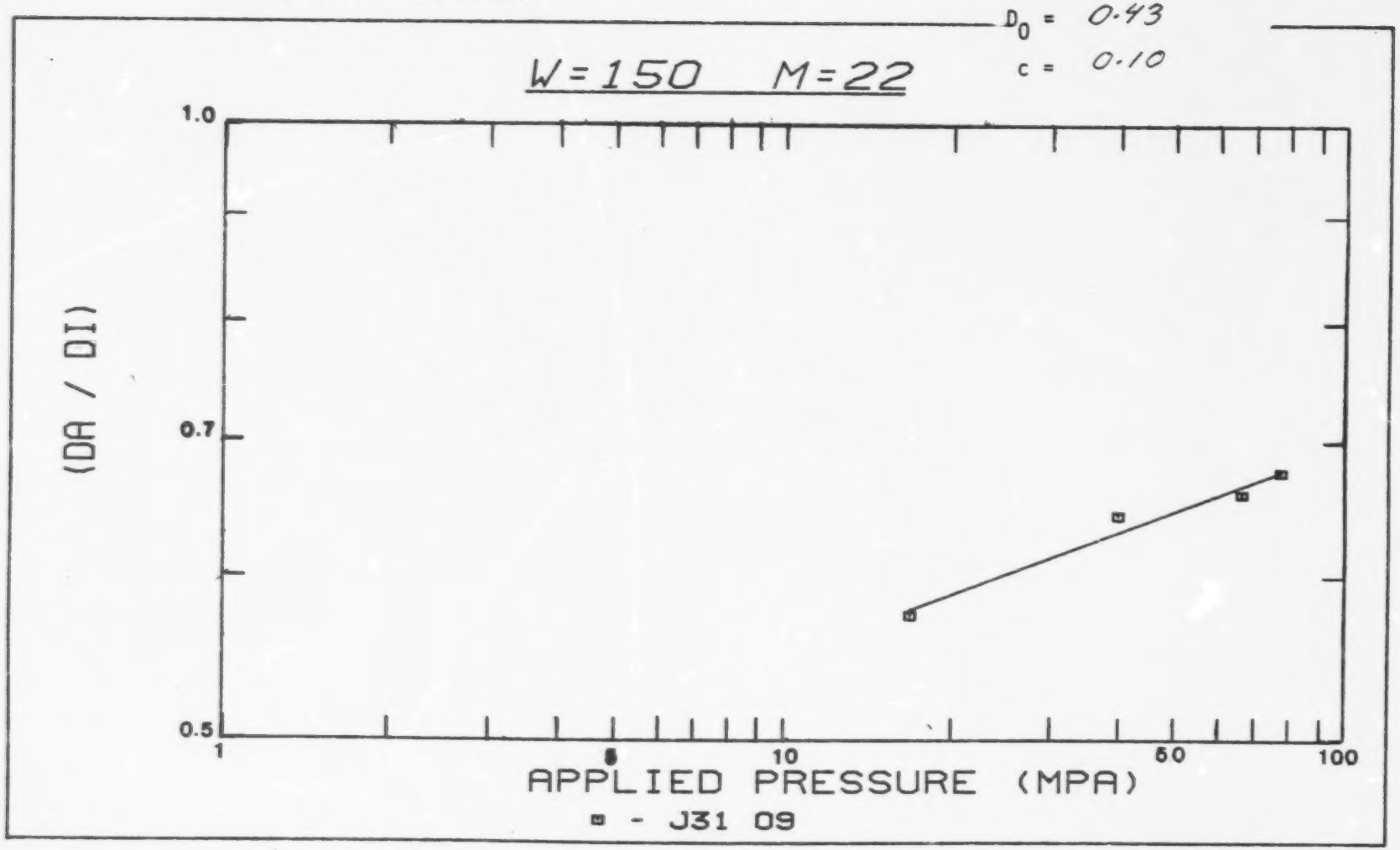
TUBE DIAMETER 500mm

PARTICLE SIZE MIXED

$D_A/D_I = D_0 P^C$

$D_0 = 0.43$

$c = 0.10$



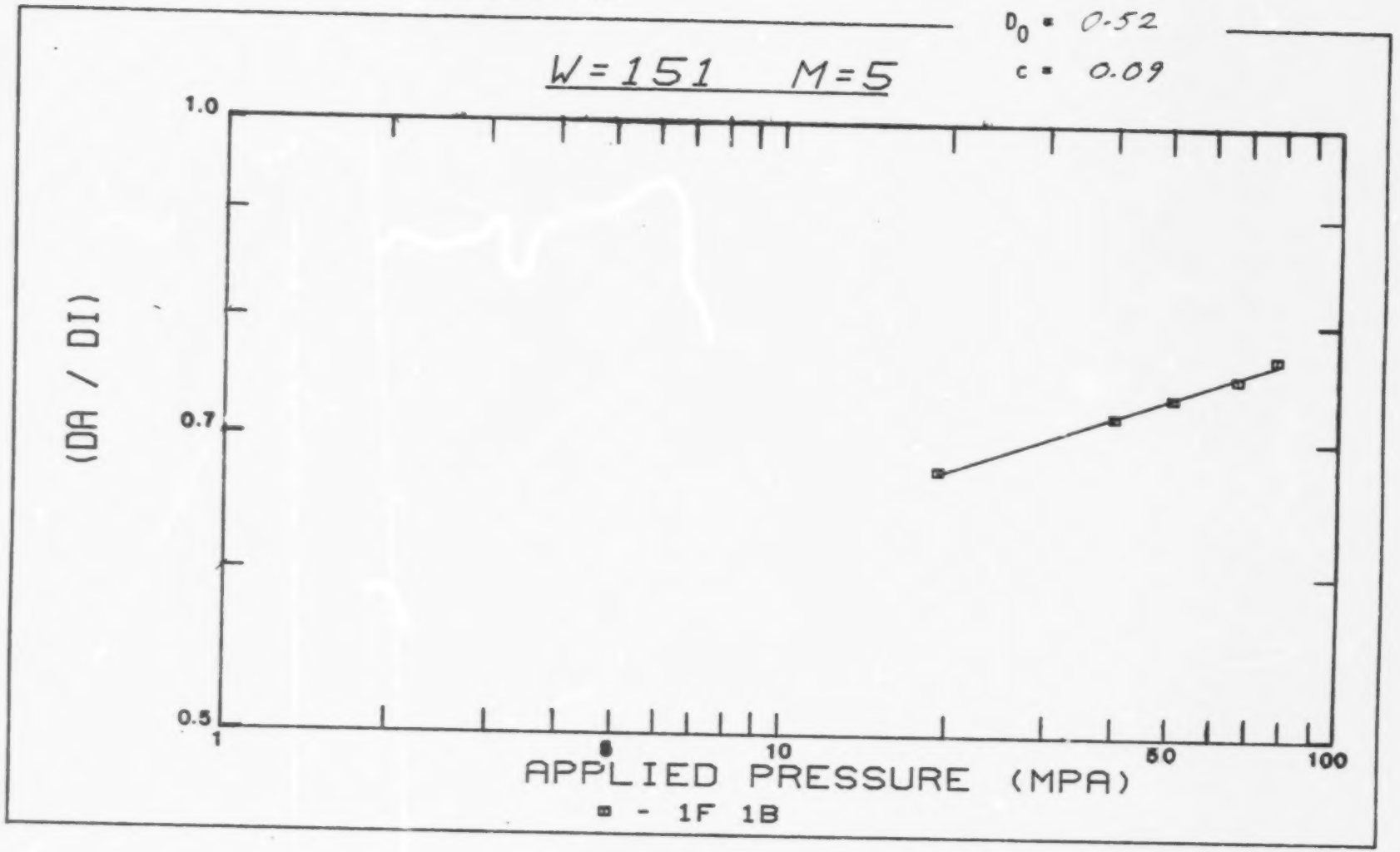
TUBE DIAMETER 500 mm

PARTICLE SIZE > 56-25 mm

$D_A/D_I = D_0 P^c$

$D_0 = 0.52$

$c = 0.09$



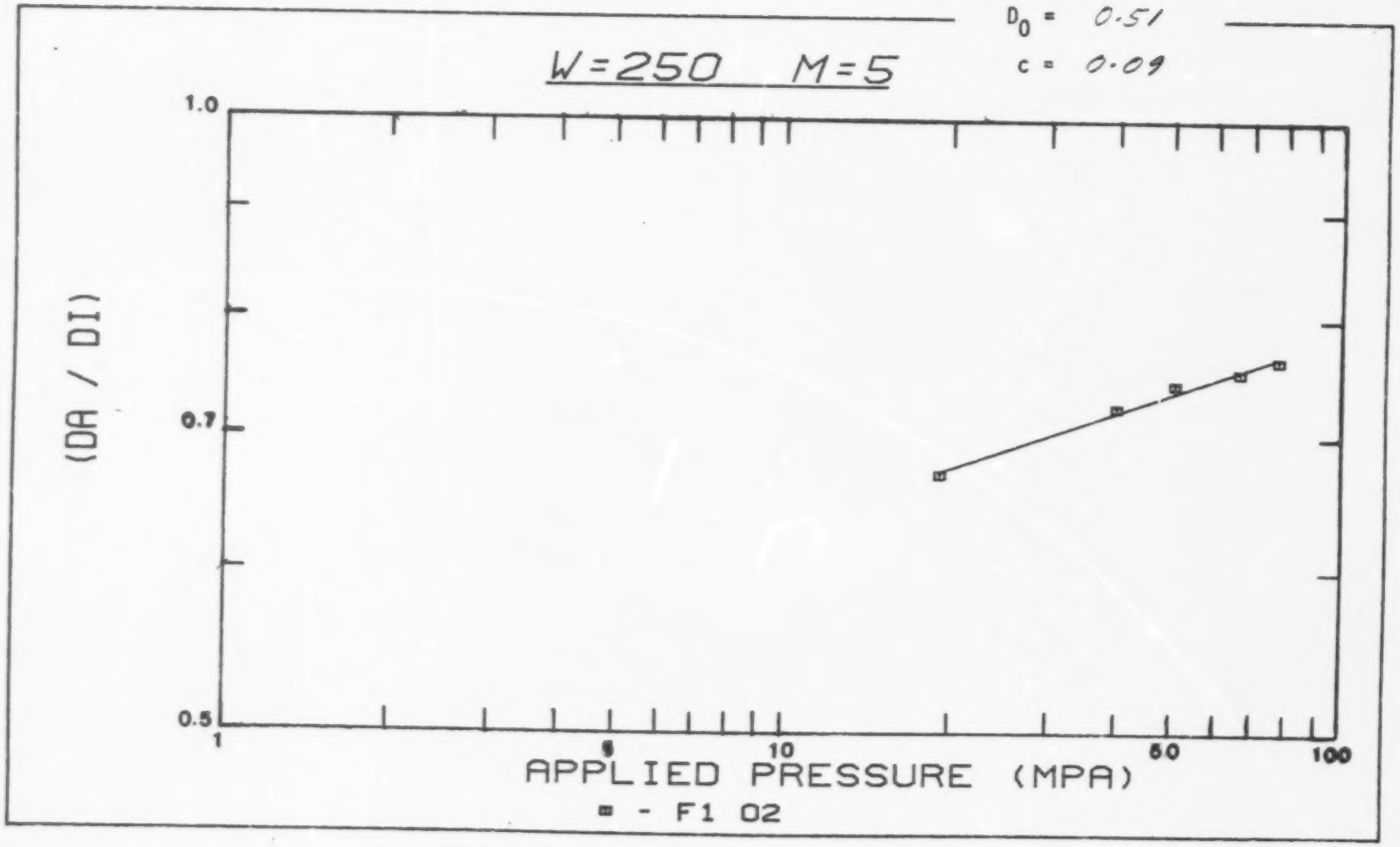
TUBE DIAMETER 500 mm

PARTICLE SIZE > 56.25 mm

$D_A/D_I = D_0 P^C$

$D_0 = 0.51$

$c = 0.09$



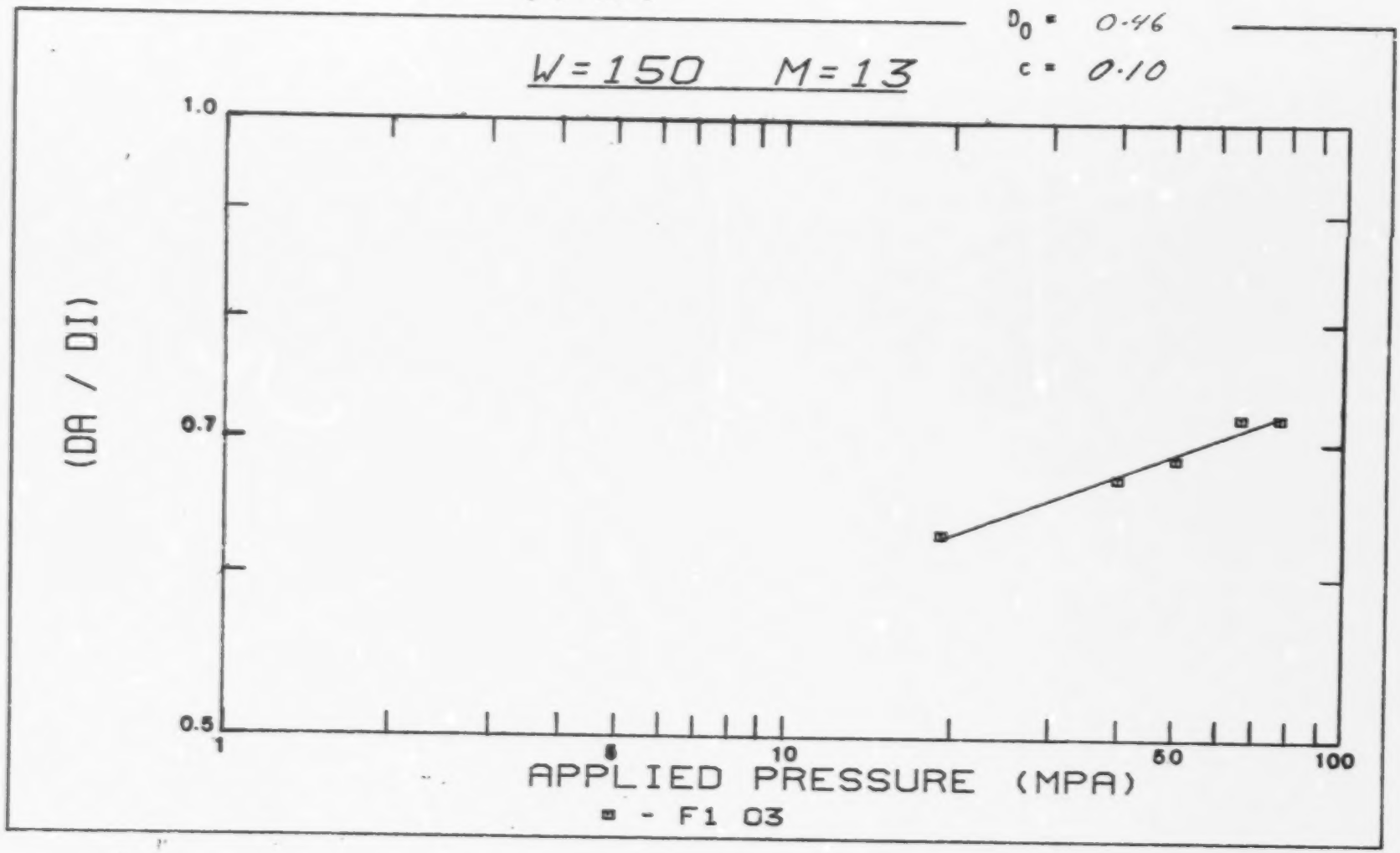
TUBE DIAMETER 500 mm

PARTICLE SIZE 56.25 - 4.76 mm

$D_A/D_I = D_0 P^C$

$D_0 = 0.46$

$c = 0.10$



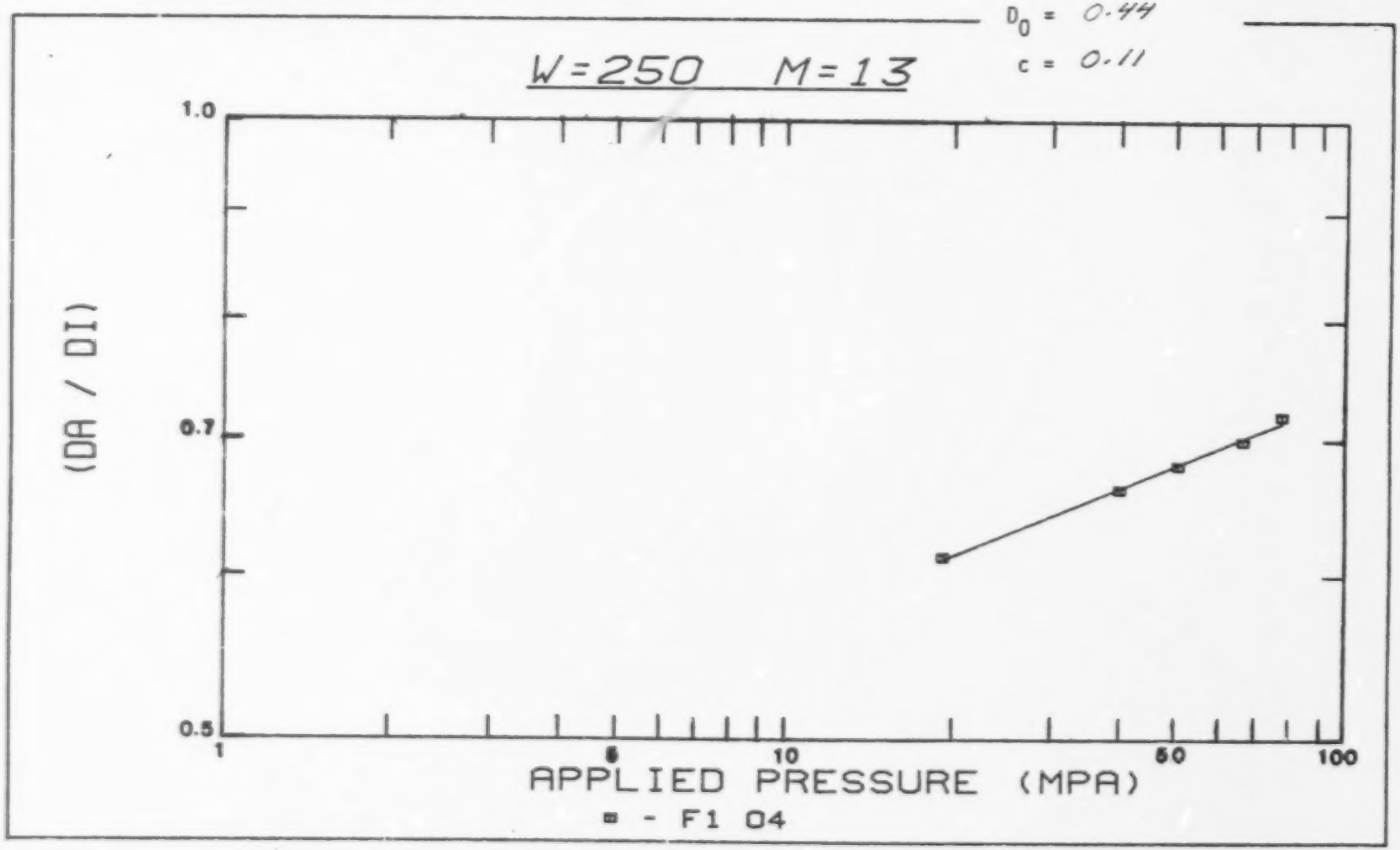
TUBE DIAMETER 500 mm

PARTICLE SIZE 56.25 - 4.76 mm

$D_A/D_I = D_0 P^C$

$D_0 = 0.44$

$c = 0.11$



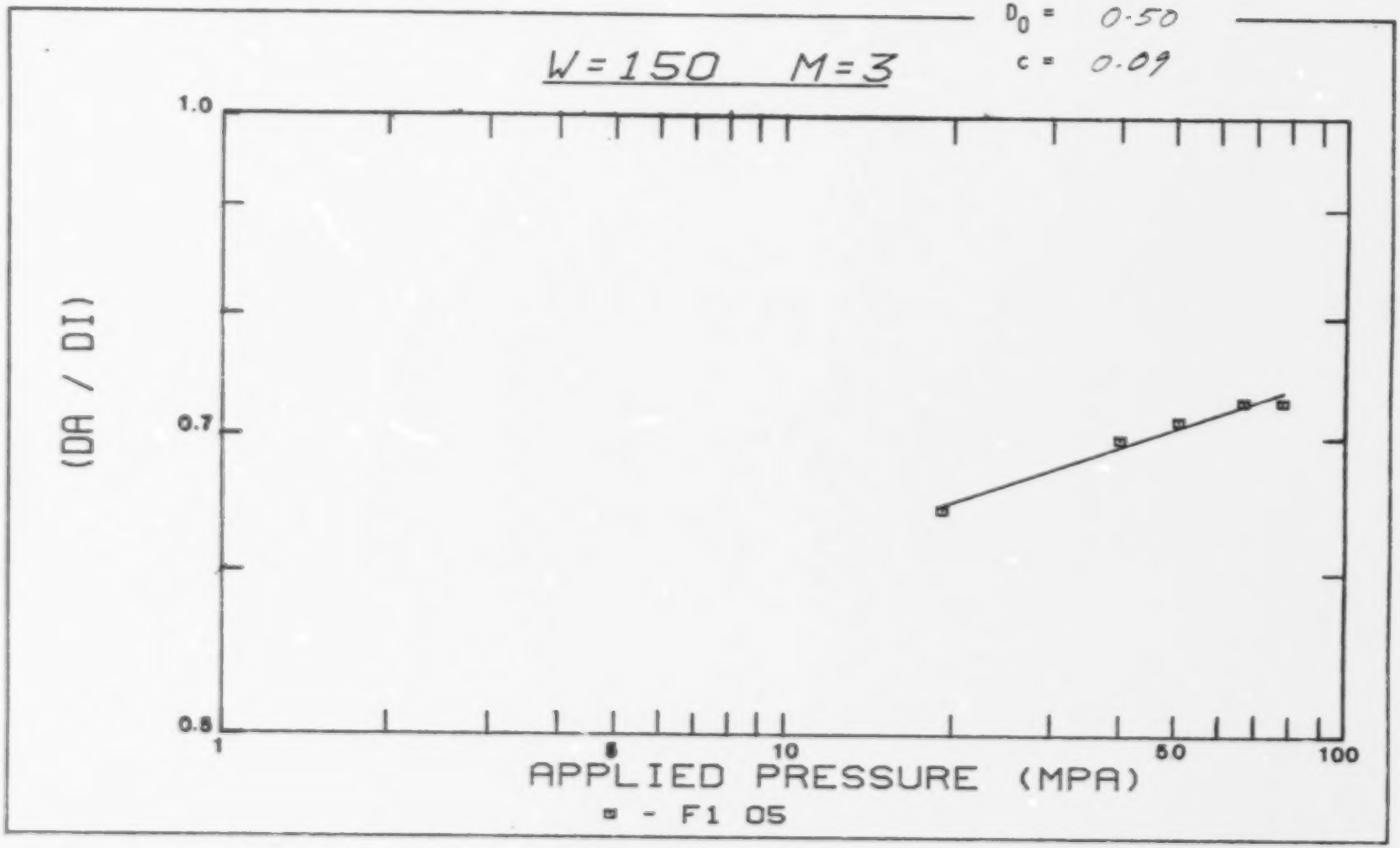
TUBE DIAMETER 500 mm

PARTICLE SIZE < 3·17

$D_A/D_I = D_0 P^C$

$D_0 =$ 0·50

$c =$ 0·09



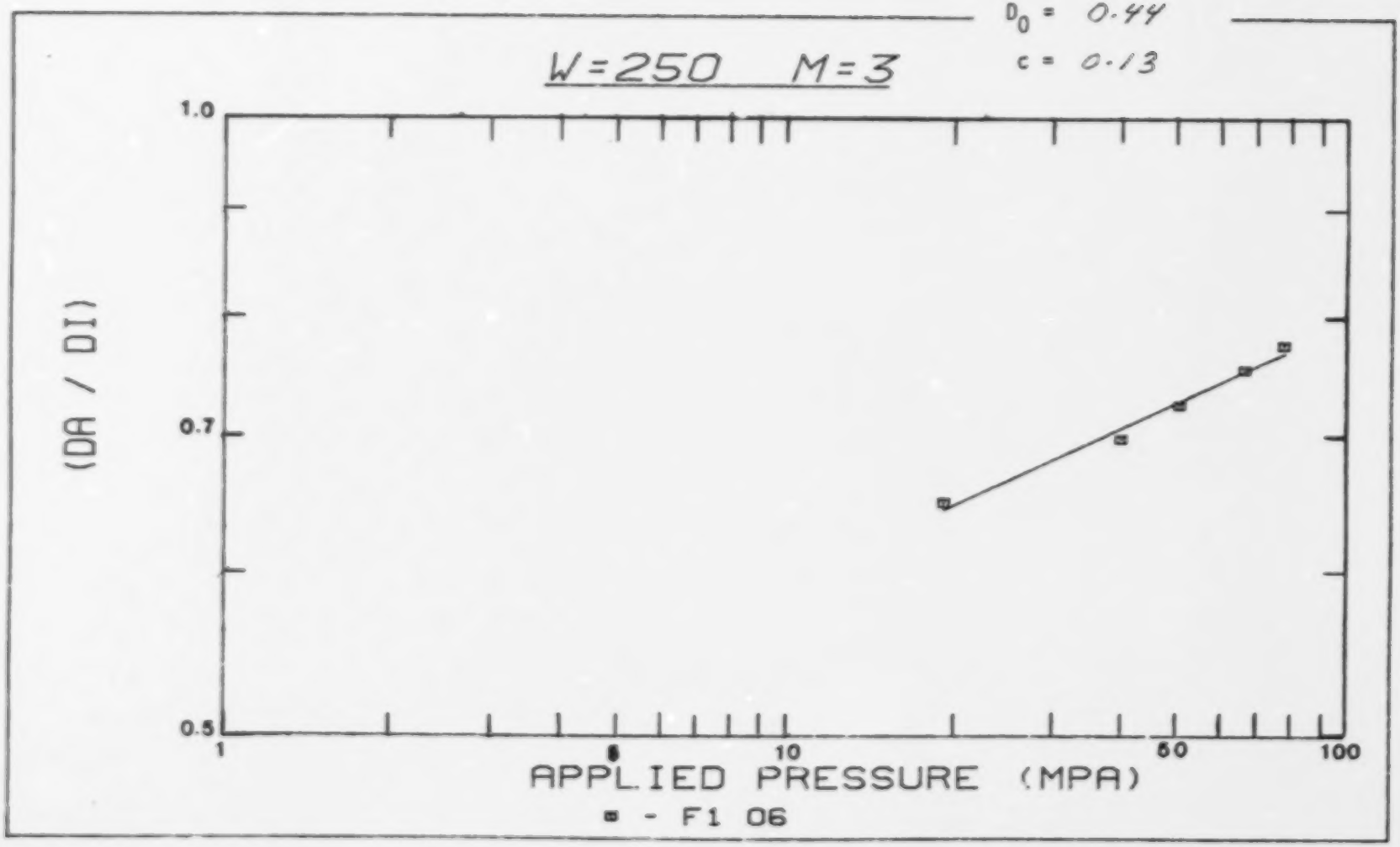
TUBE DIAMETER 500mm

PARTICLE SIZE < 3.17

$D_A/D_I = D_0 P^C$

$D_0 = 0.44$

$c = 0.13$



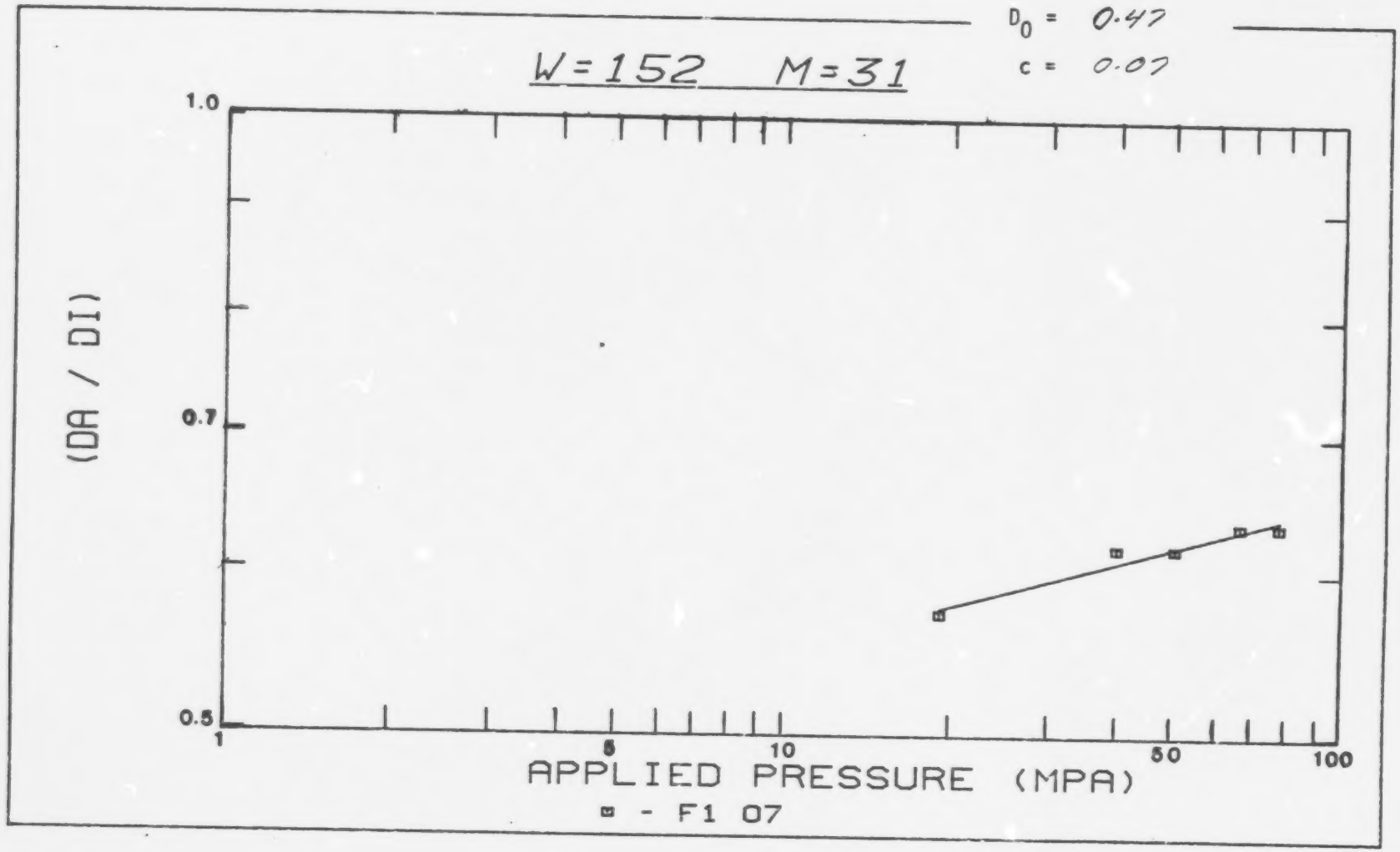
TUBE DIAMETER 500mm

PARTICLE SIZE > 56.25 mm

$D_A/D_I = D_0 P^c$

$D_0 = 0.47$

$c = 0.07$



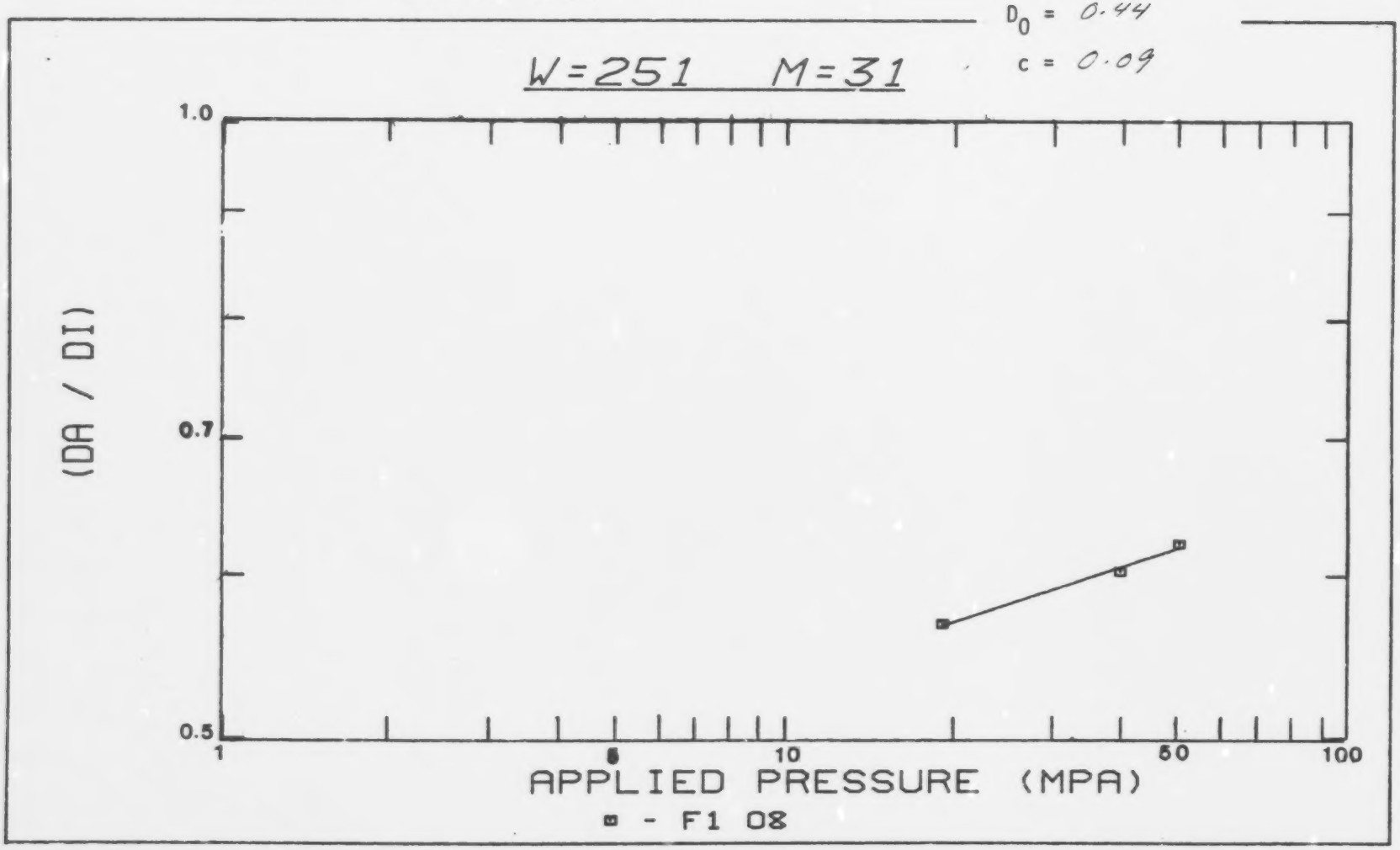
TUBE DIAMETER 500 m

PARTICLE SIZE >56.25 mm

$D_A/D_I = D_0 P^c$

D_0 = 0.44

c = 0.09



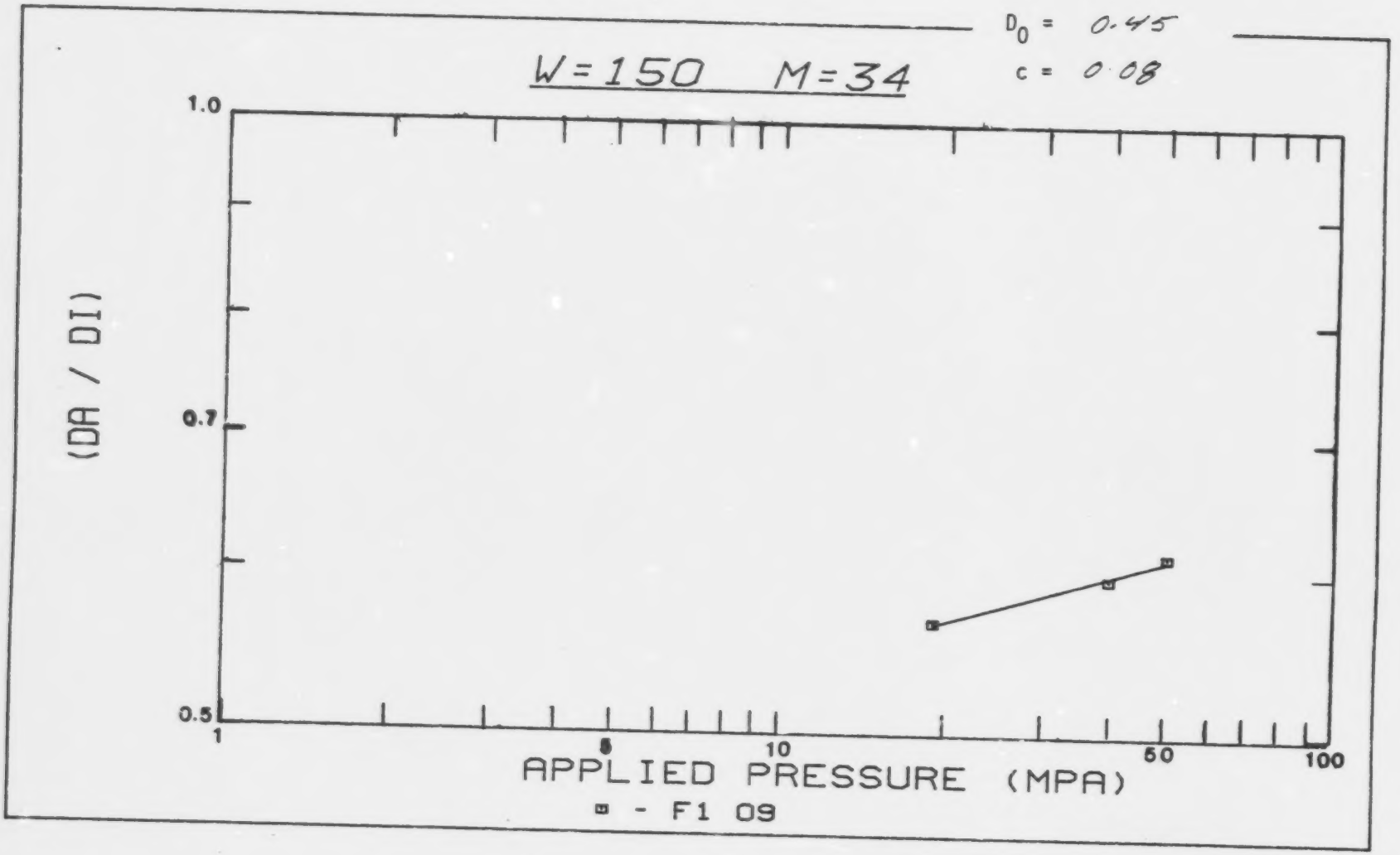
TUBE DIAMETER 500 mm

PARTICLE SIZE 56.25 - 4.76 mm

$D_A/D_I = D_0 P^C$

$D_0 = 0.45$

$c = 0.08$



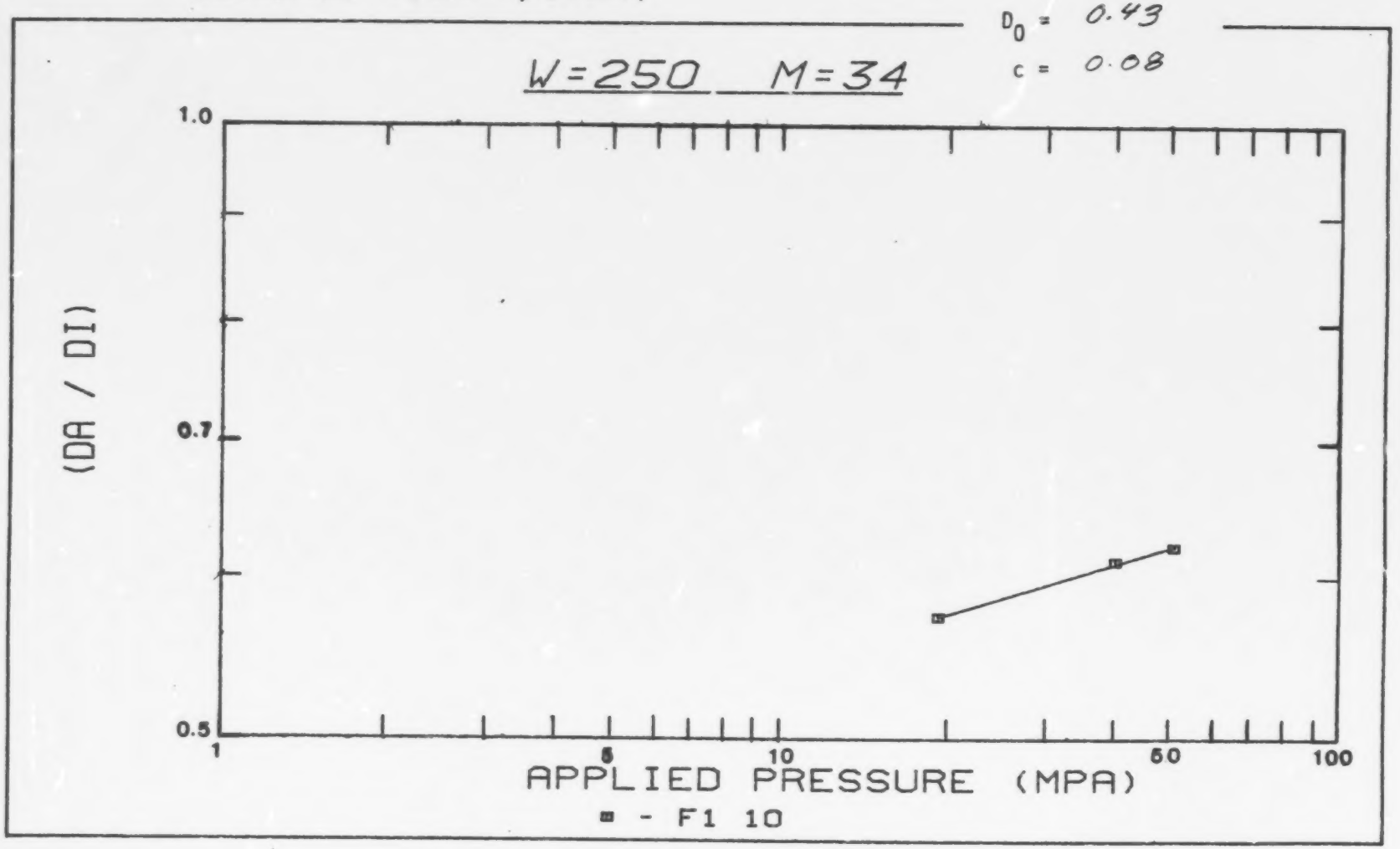
TUBE DIAMETER 500 mm

PARTICLE SIZE 56·25 - 4.76 mm

$D_A/D_I = D_0 P^c$

$D_0 = 0.43$

$c = 0.08$



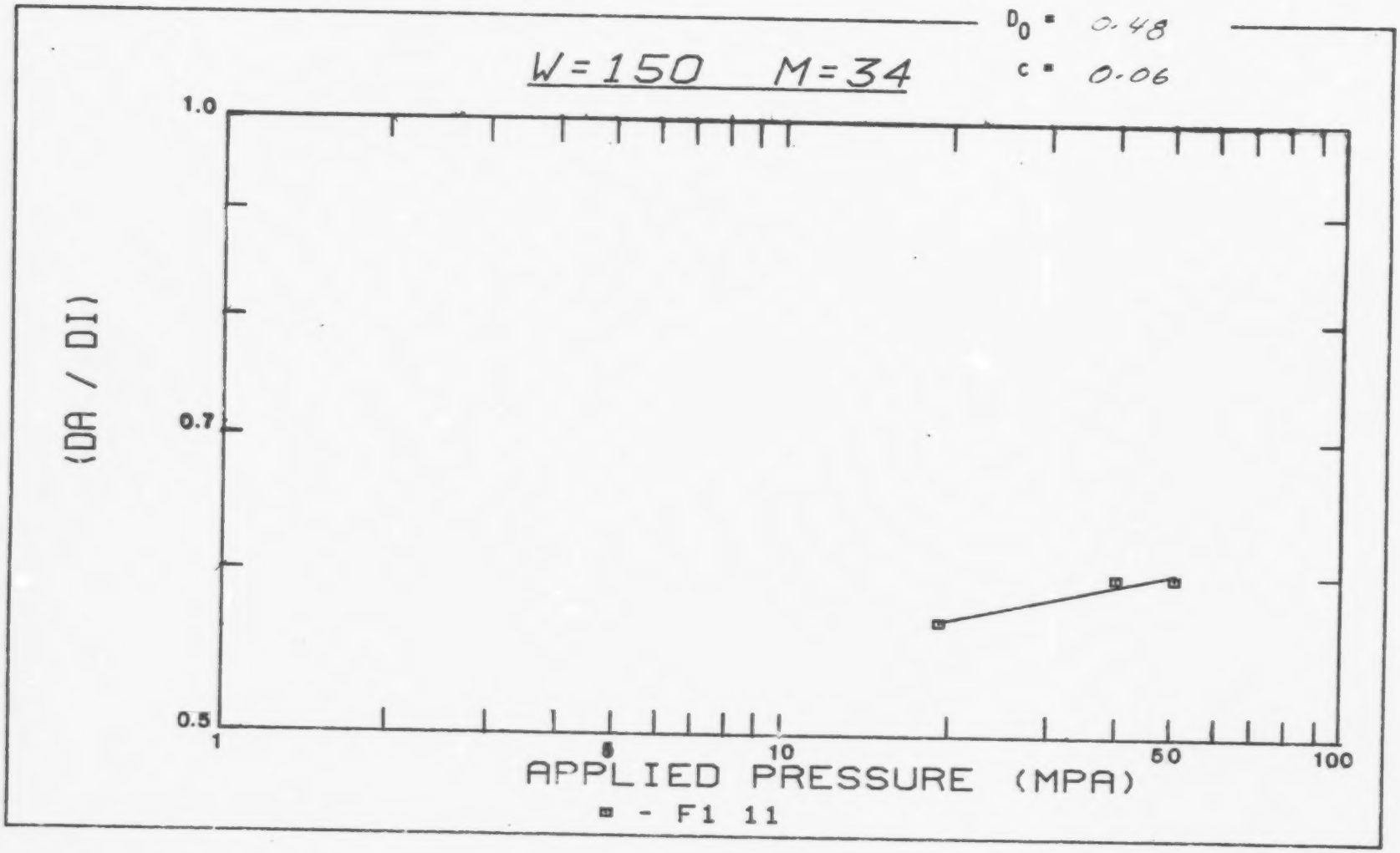
TUBE DIAMETER 500 mm

PARTICLE SIZE 4.76 - 3.17 mm

$D_A/D_I = D_0\ P^c$

$D_0 =$ 0.48

$c =$ 0.06



TUBE DIAMETER 500 mm

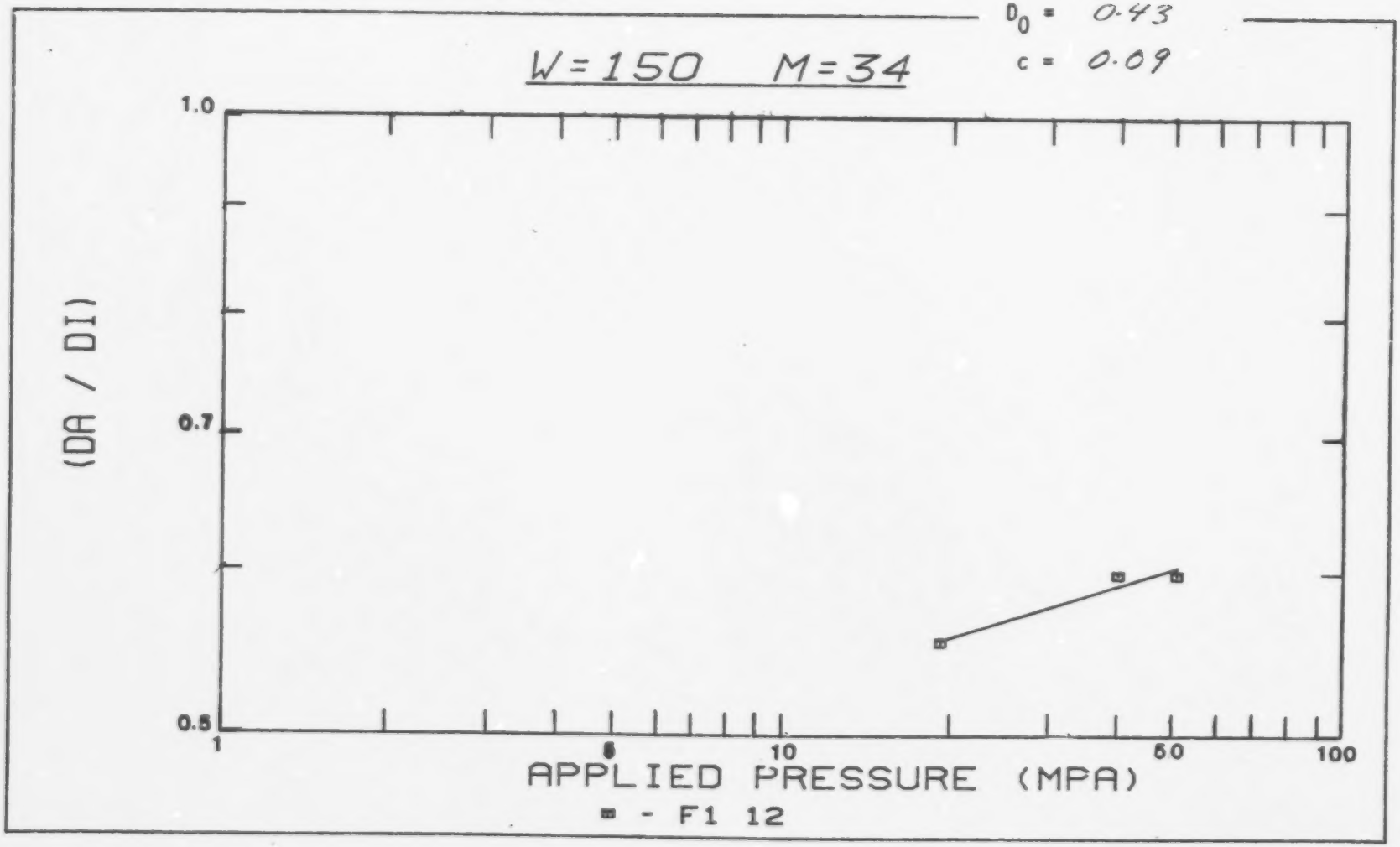
PARTICLE SIZE < 3.17 mm

$D_A/D_I = D_0 P^c$

$D_0 = 0.43$

$c = 0.09$

W = 150 M = 34

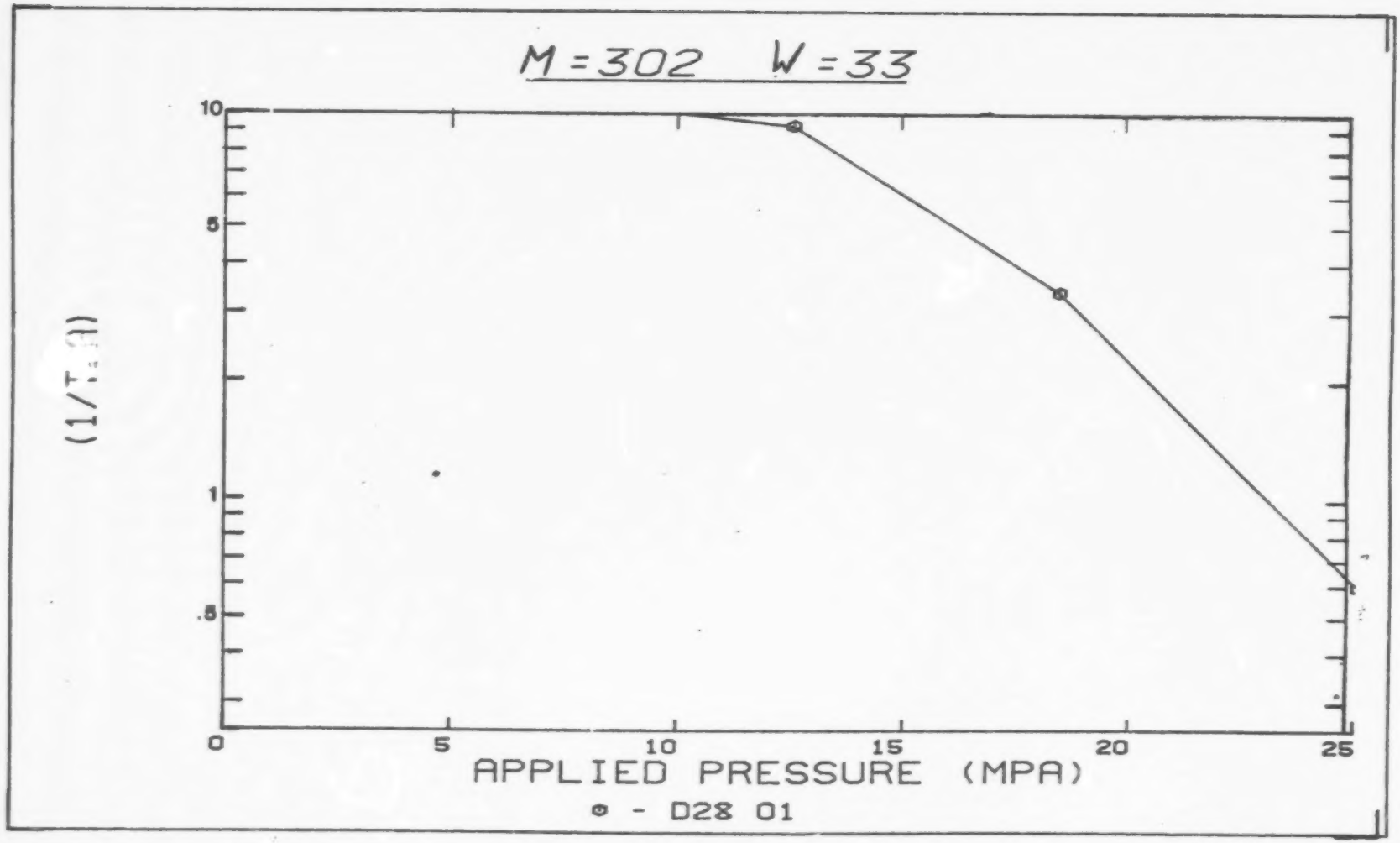


bc

GAS PERMIABILITY VS APPLIED PRESSURE

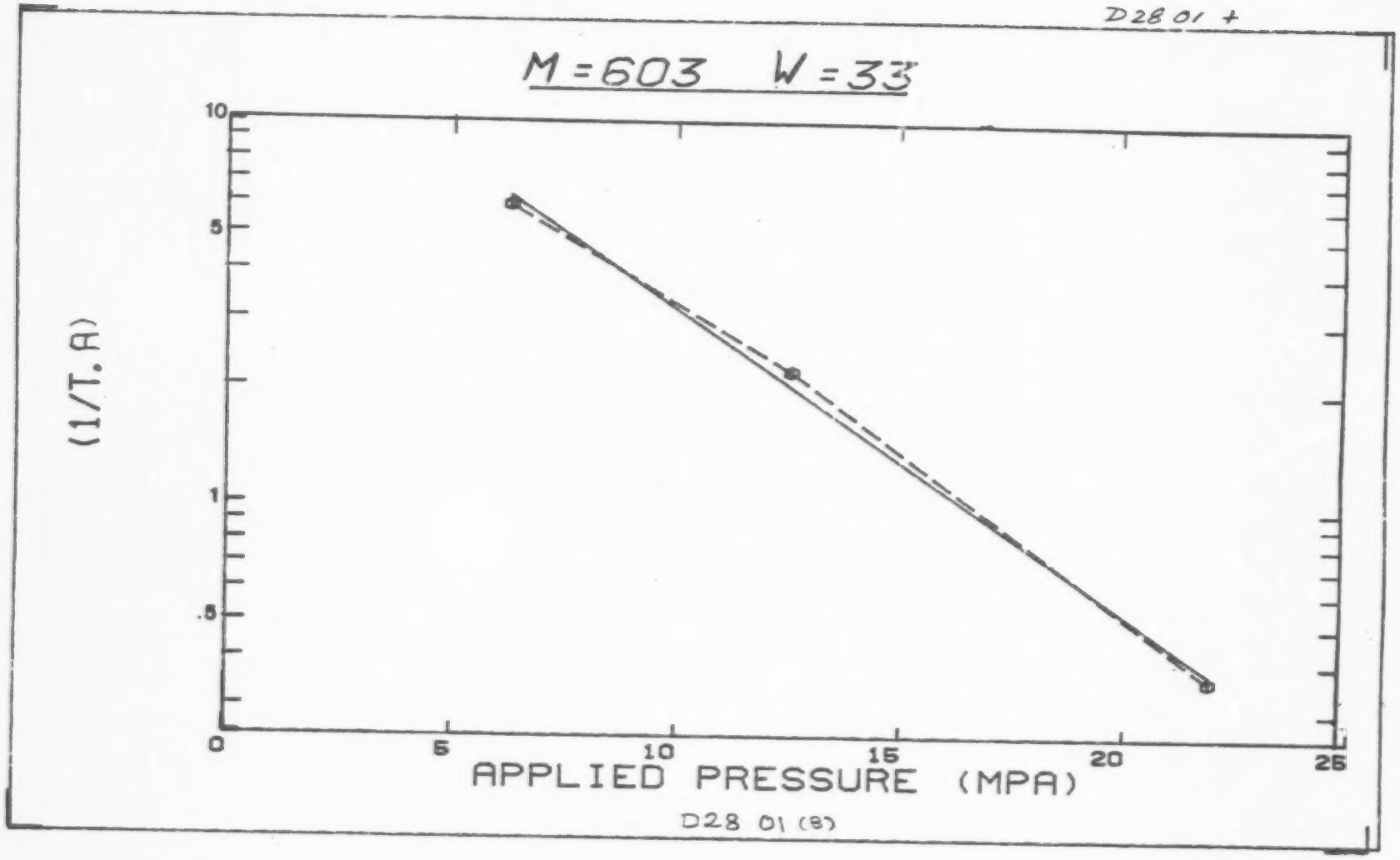
TUBE DIAMETER 880mm TAPER

PARTICLE SIZE AS RECEIVED



TUBE DIAMETER 880 mm TAPER

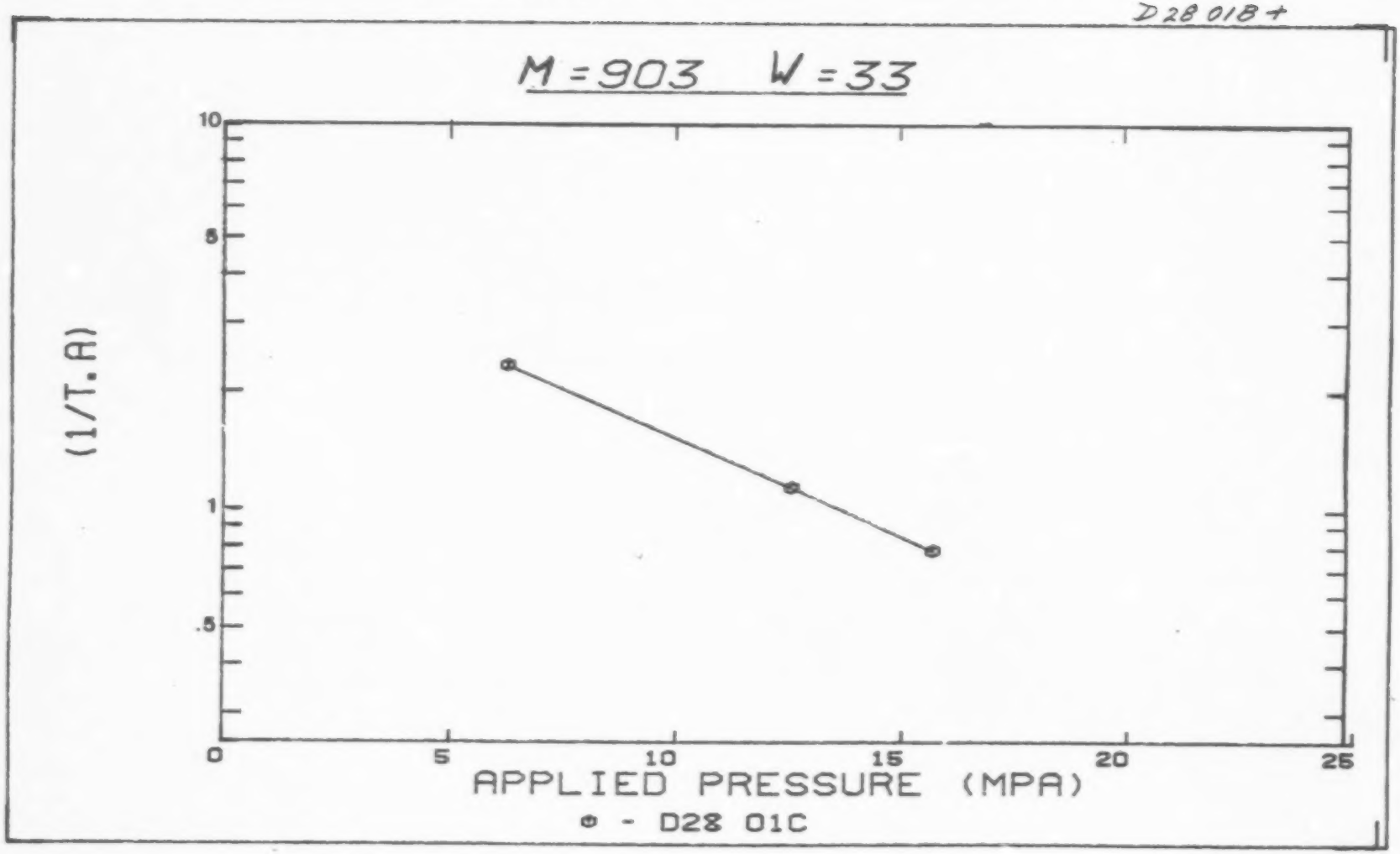
PARTICLE SIZE AS RECEIVED



TUBE DIAMETER 880mm TAPER

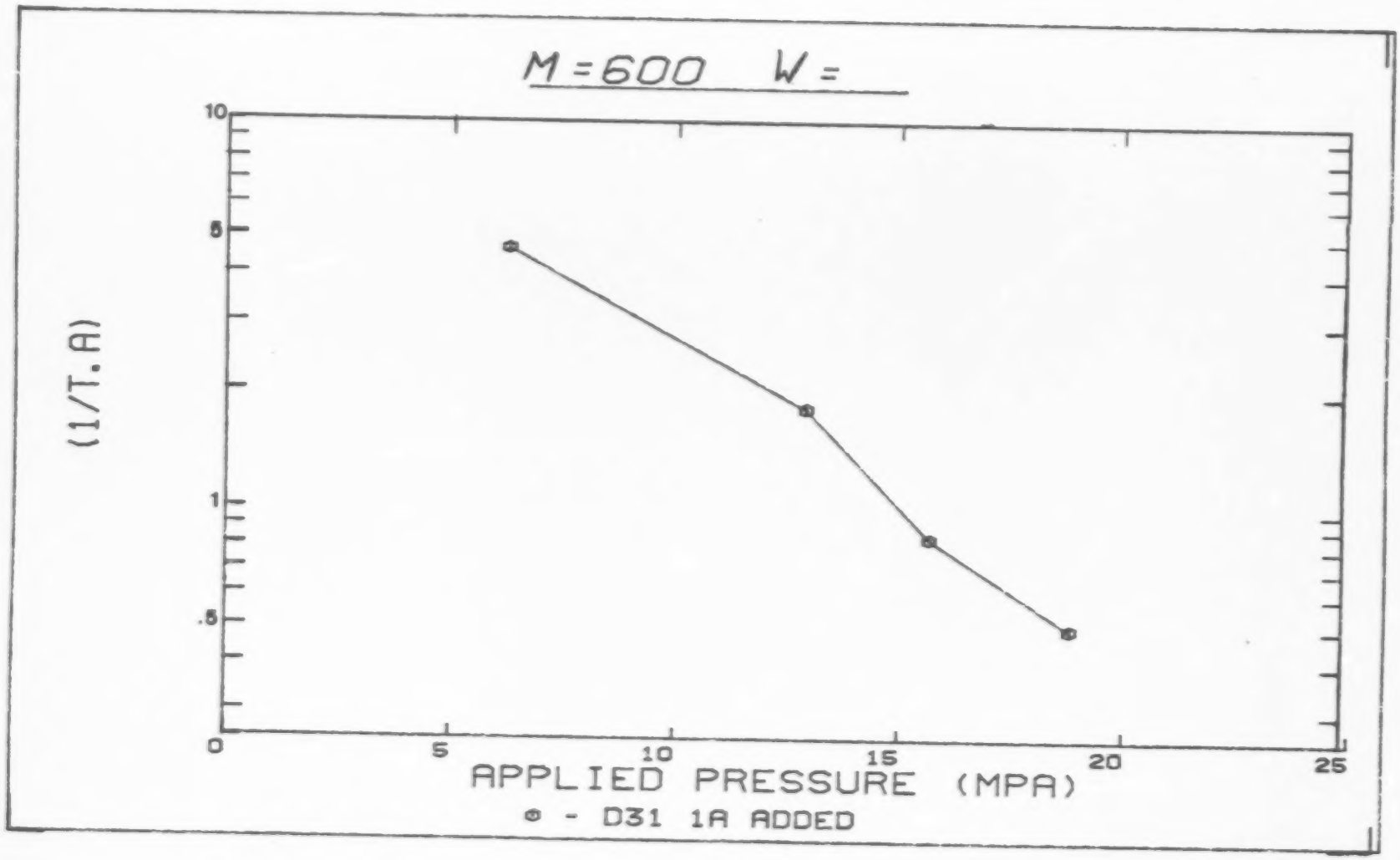
PARTICLE SIZE AS RECEIVED

D28 01B+



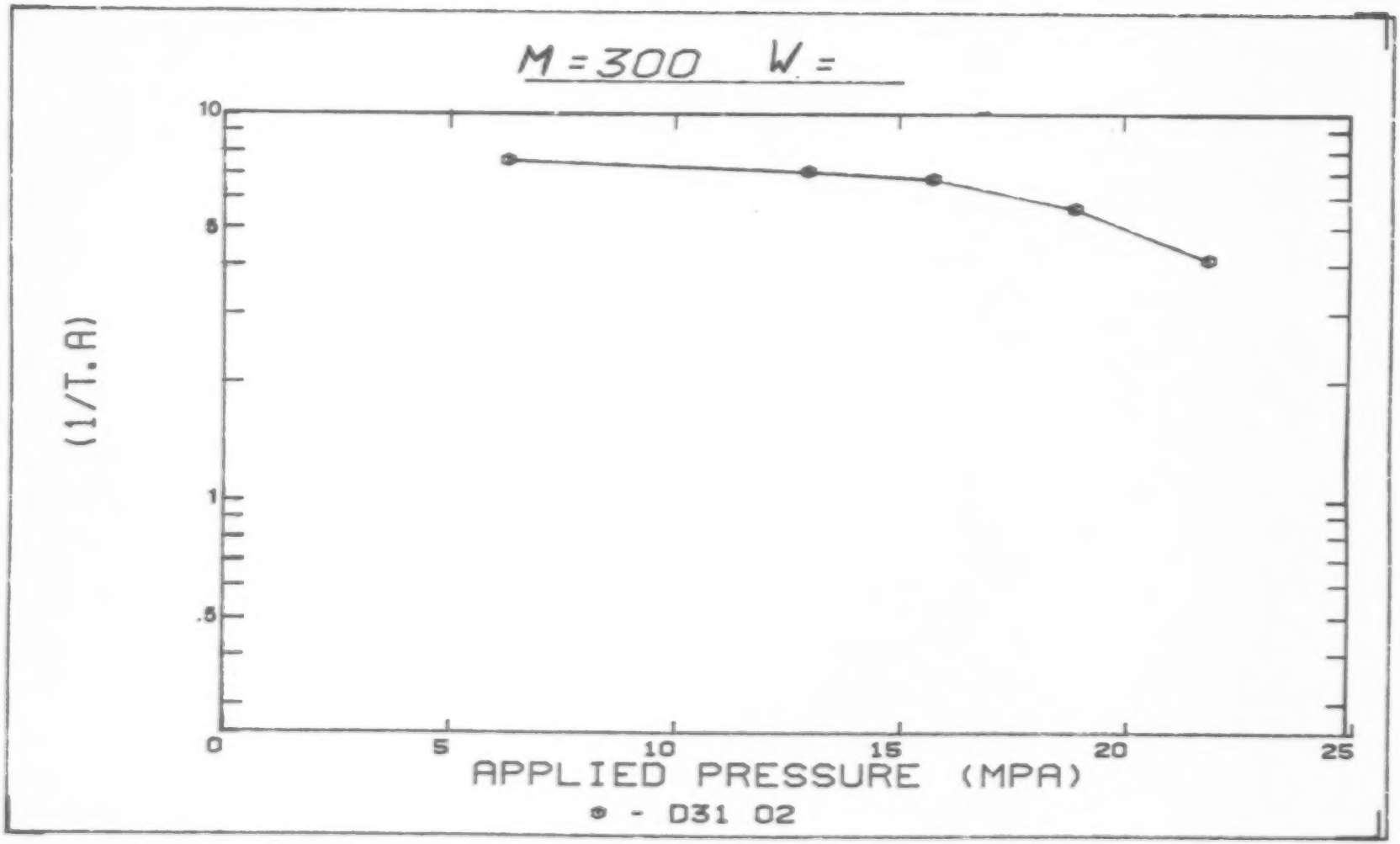
TUBE DIAMETER 880mm TAPER

PARTICLE SIZE < 6·35 mm



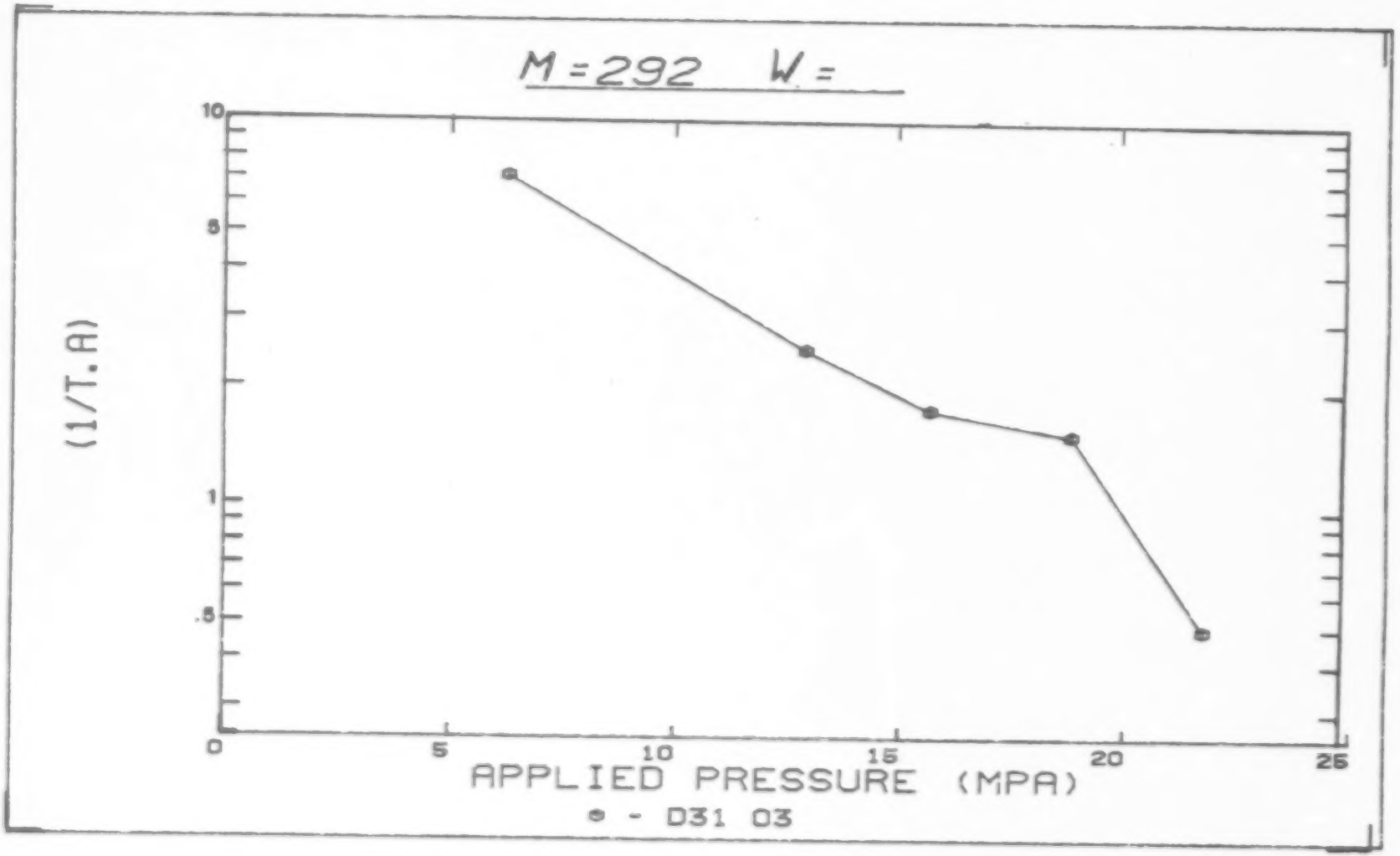
TUBE DIAMETER 880mm TAPER

PARTICLE SIZE 12·7 mm AVERAGE



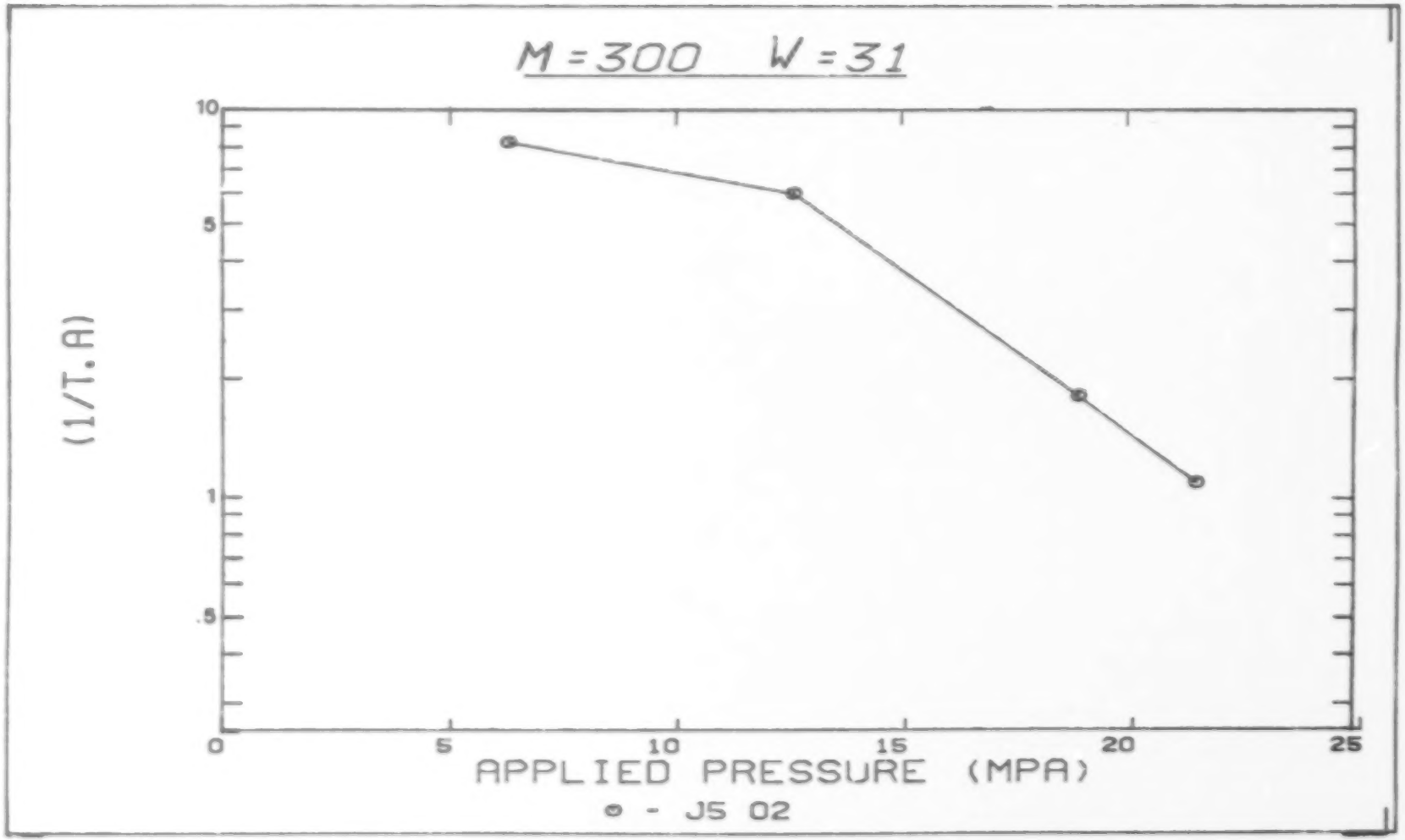
TUBE DIAMETER 880 mm TAPER

PARTICLE SIZE < 3-17 mm



TUBE DIAMETER 880mm

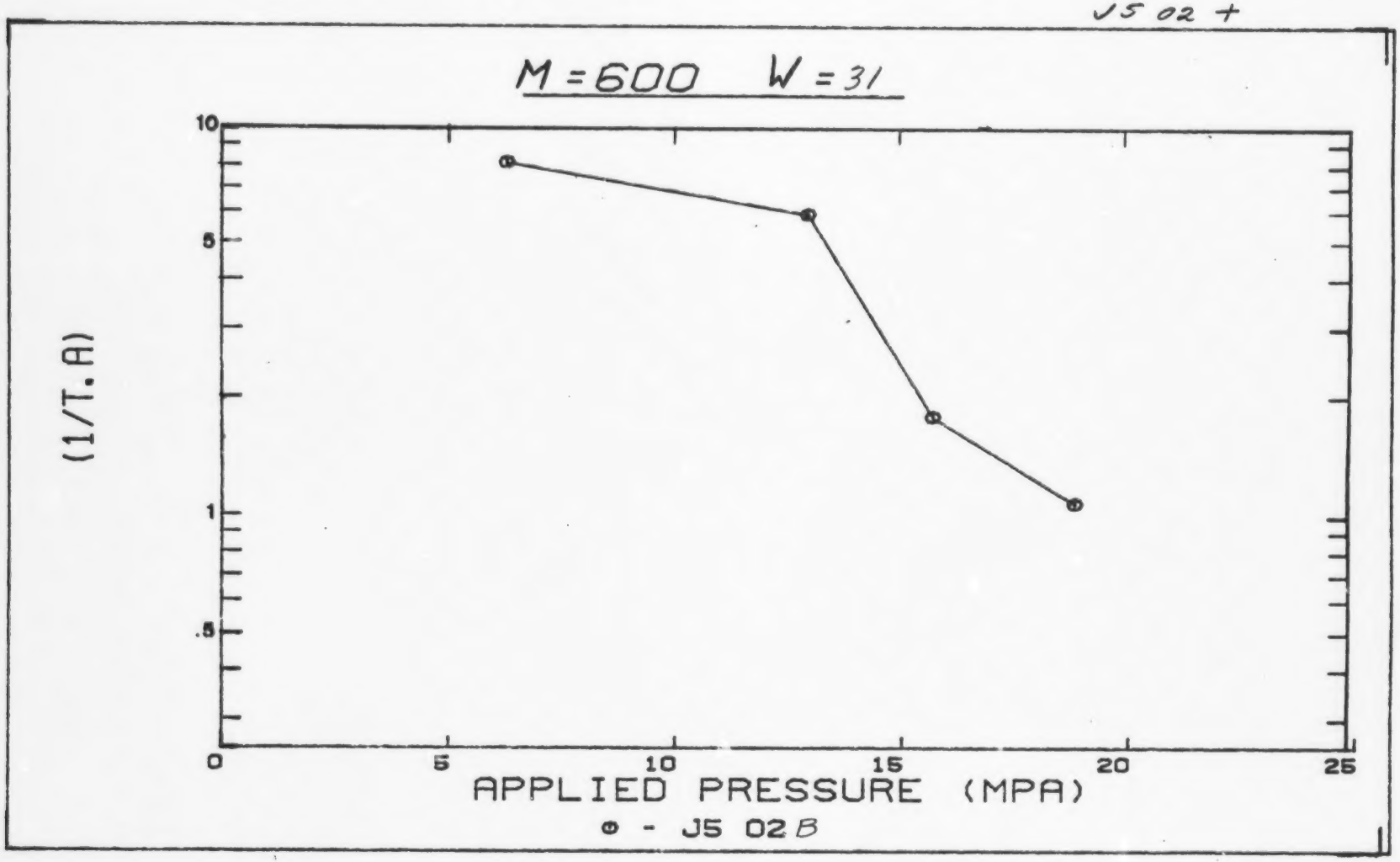
PARTICLE SIZE 56.25 — 4.76 mm



TUBE DIAMETER 880 mm

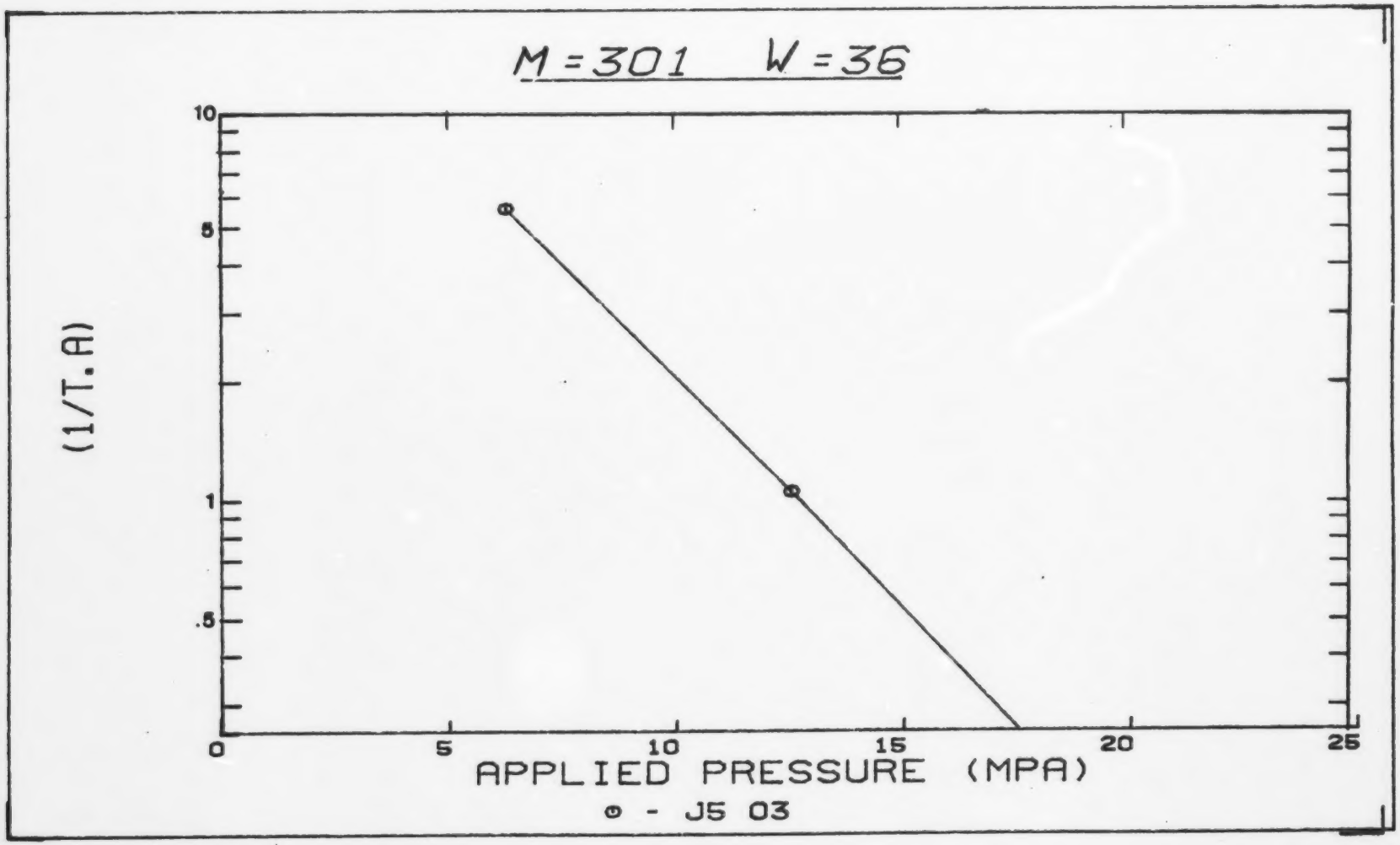
PARTICLE SIZE 56·25 - 4.76 mm

J5 02 +



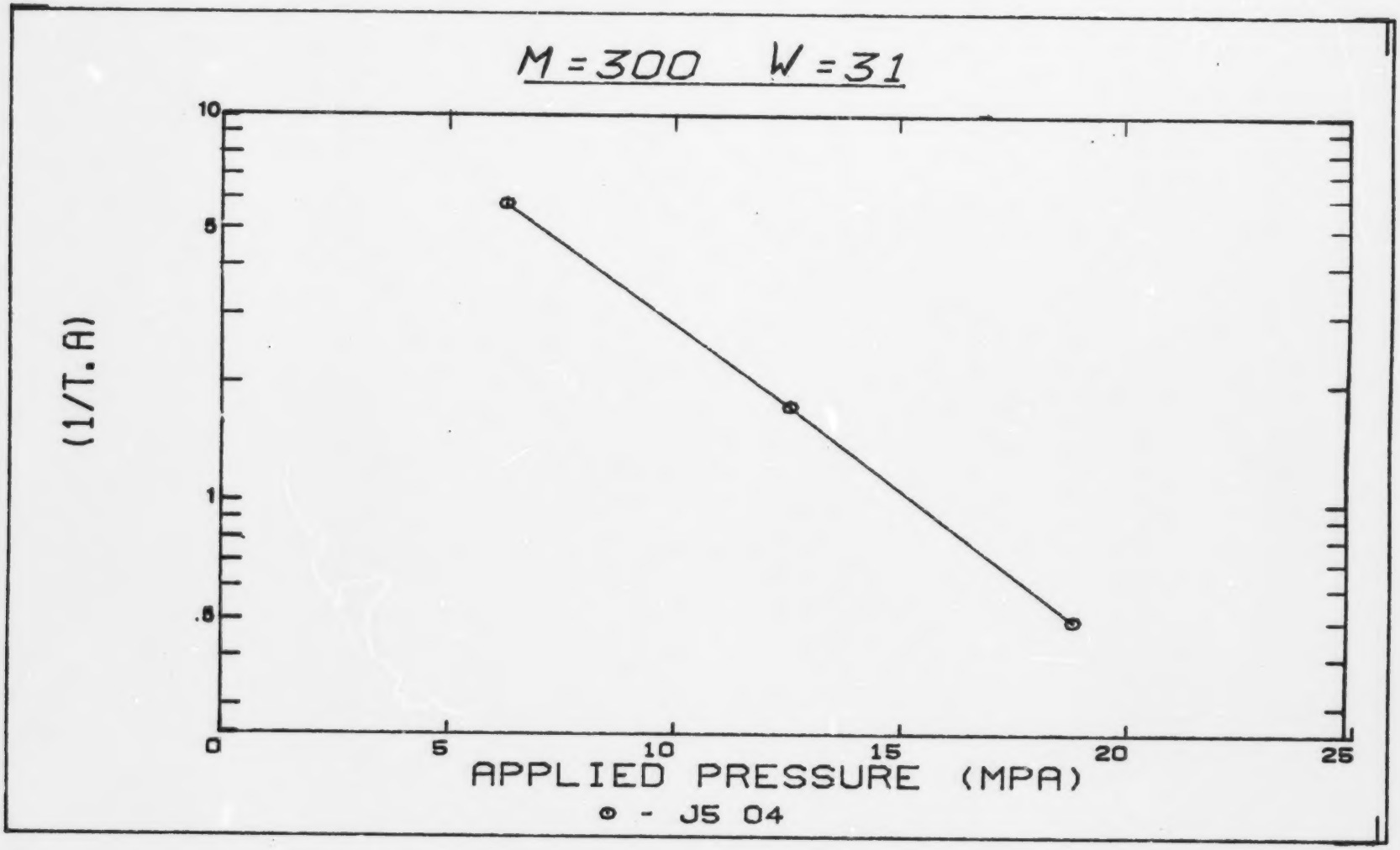
TUBE DIAMETER 880 mm

PARTICLE SIZE < 4.76 mm



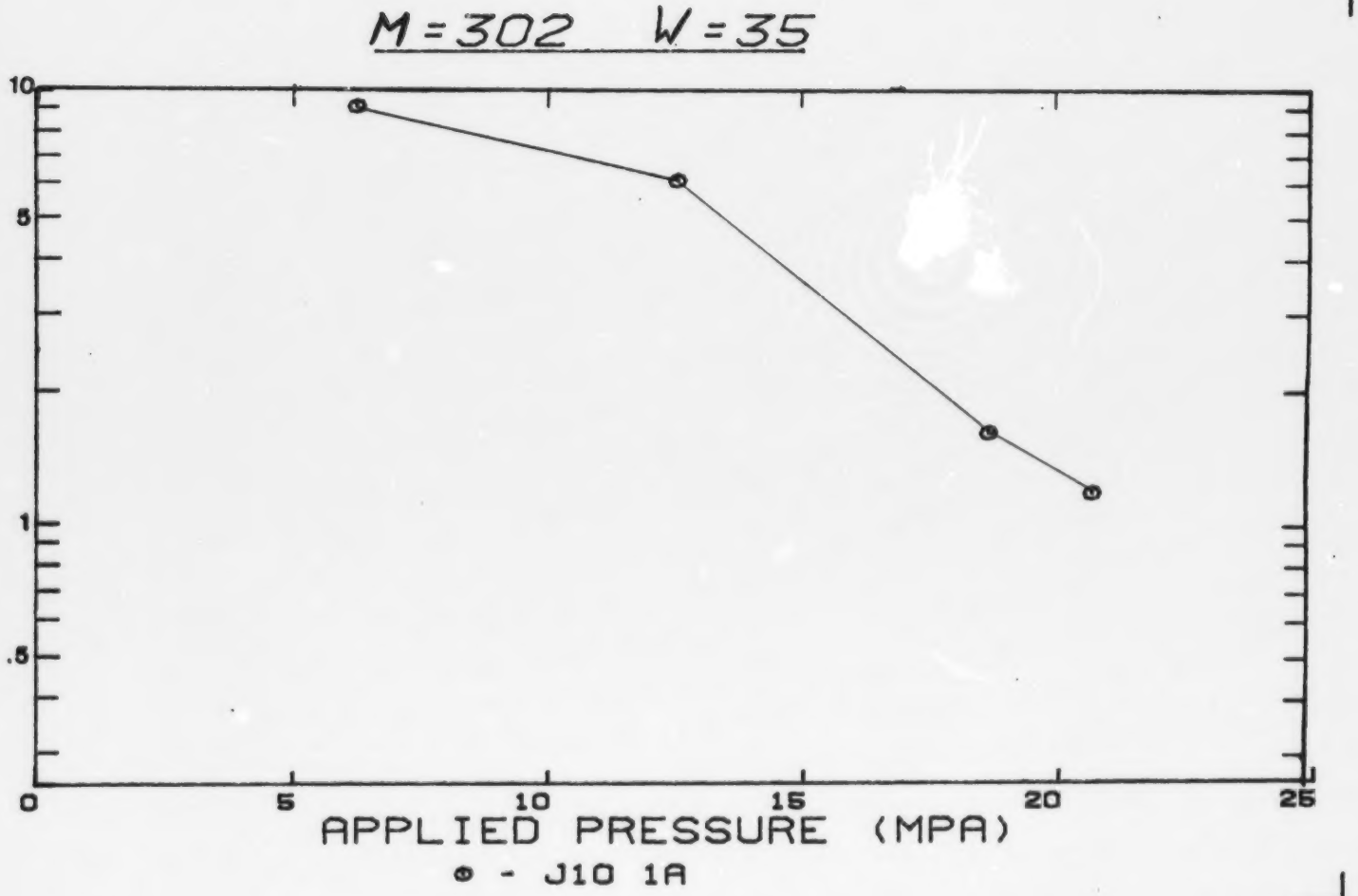
TUBE DIAMETER 880 mm

PARTICLE SIZE < 3.17 mm



TUBE DIAMETER 880.mm

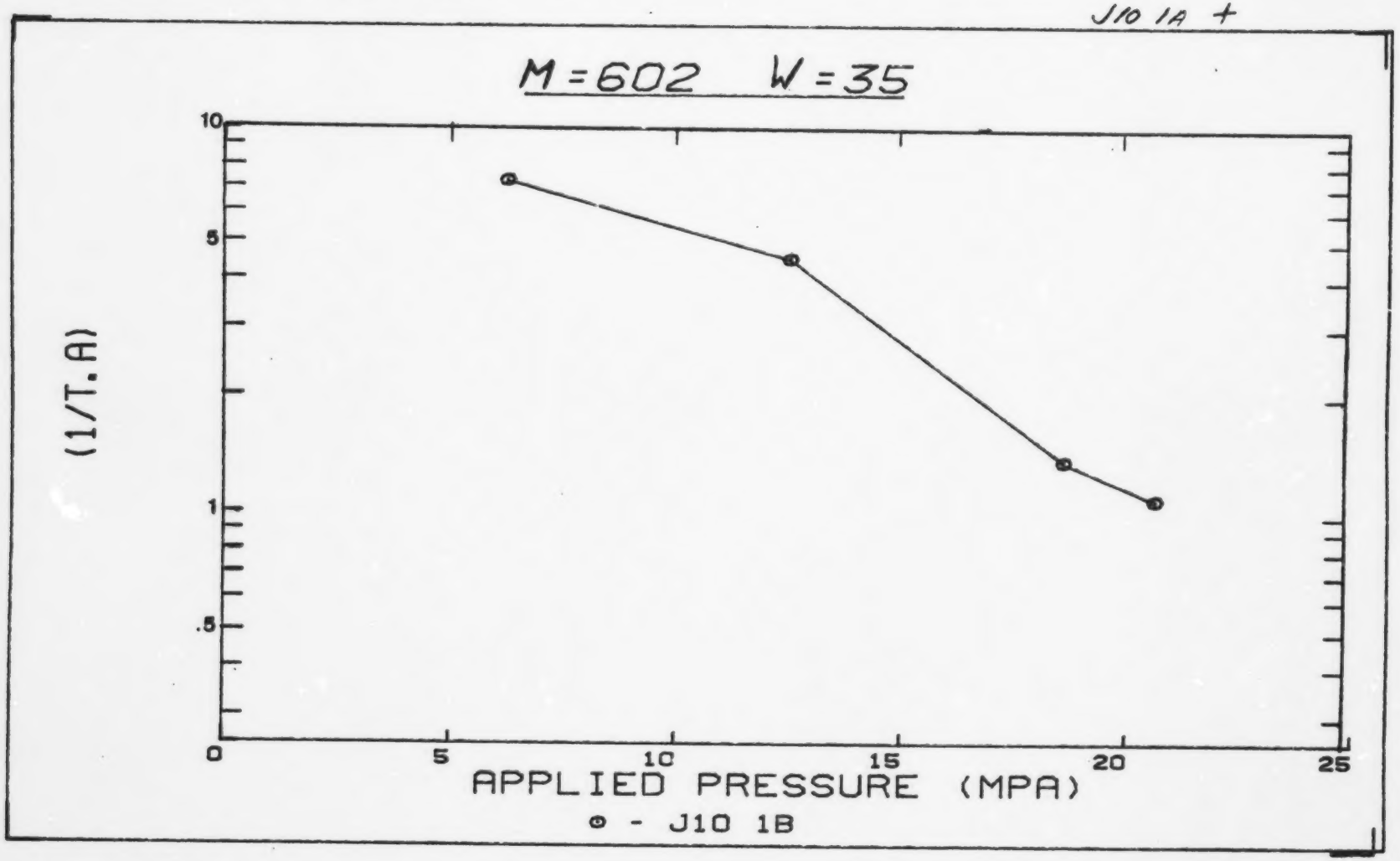
PARTICLE SIZE > 56.25 mm



TUBE DIAMETER 880 mm

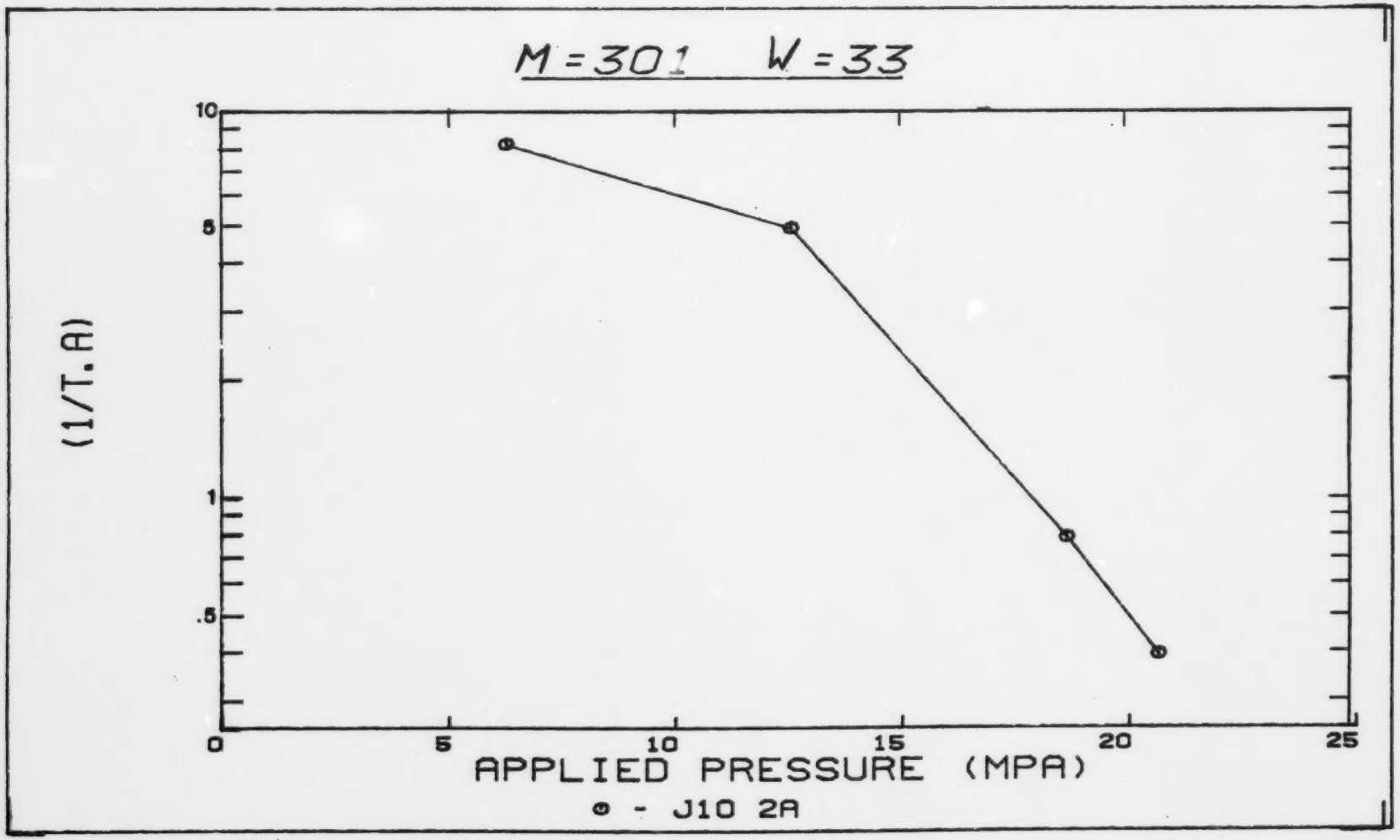
PARTICLE SIZE > 56·25

J10 1A +



TUBE DIAMETER 880mm

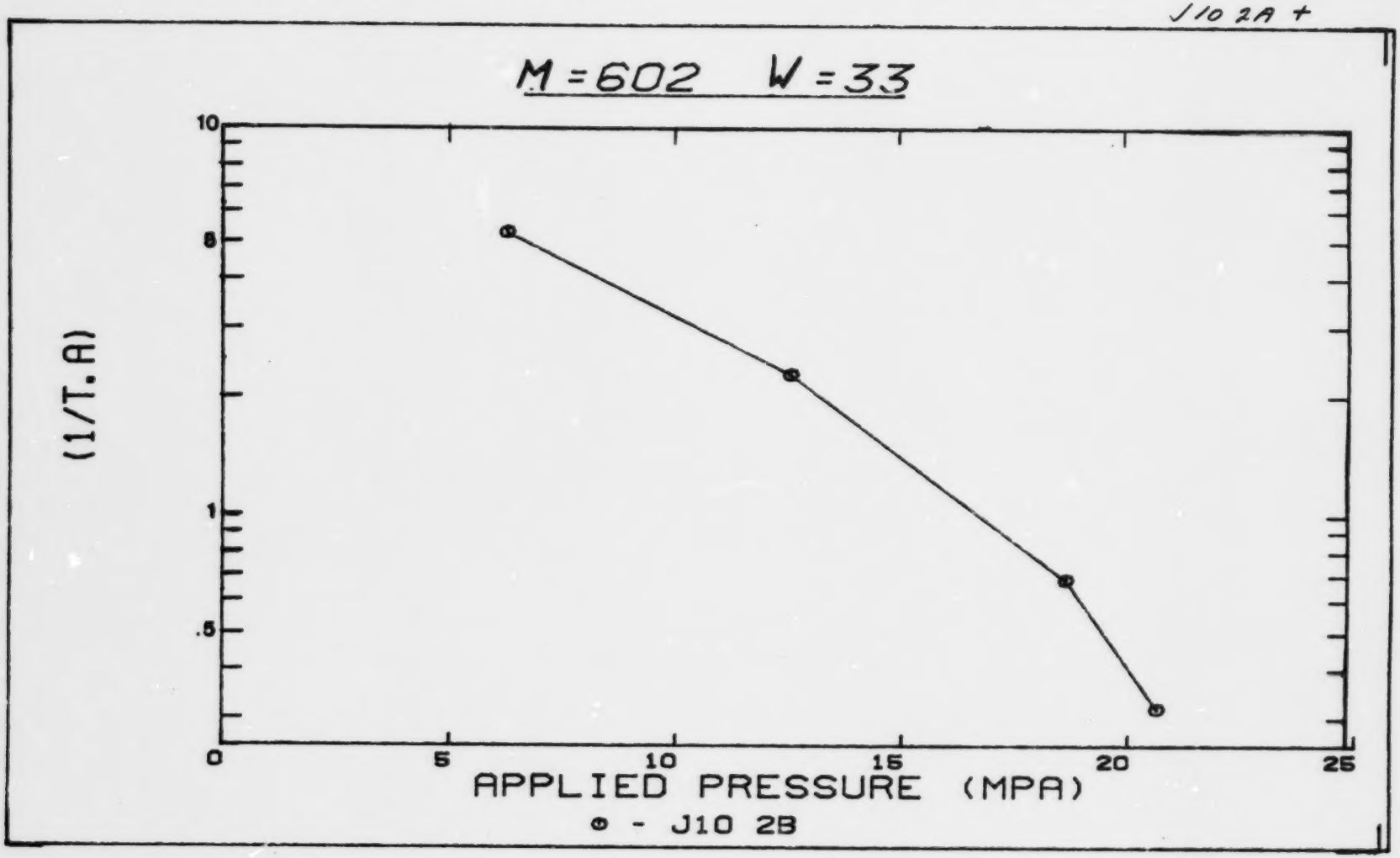
PARTICLE SIZE 56·25 – 6·35 mm



TUBE DIAMETER 880mm

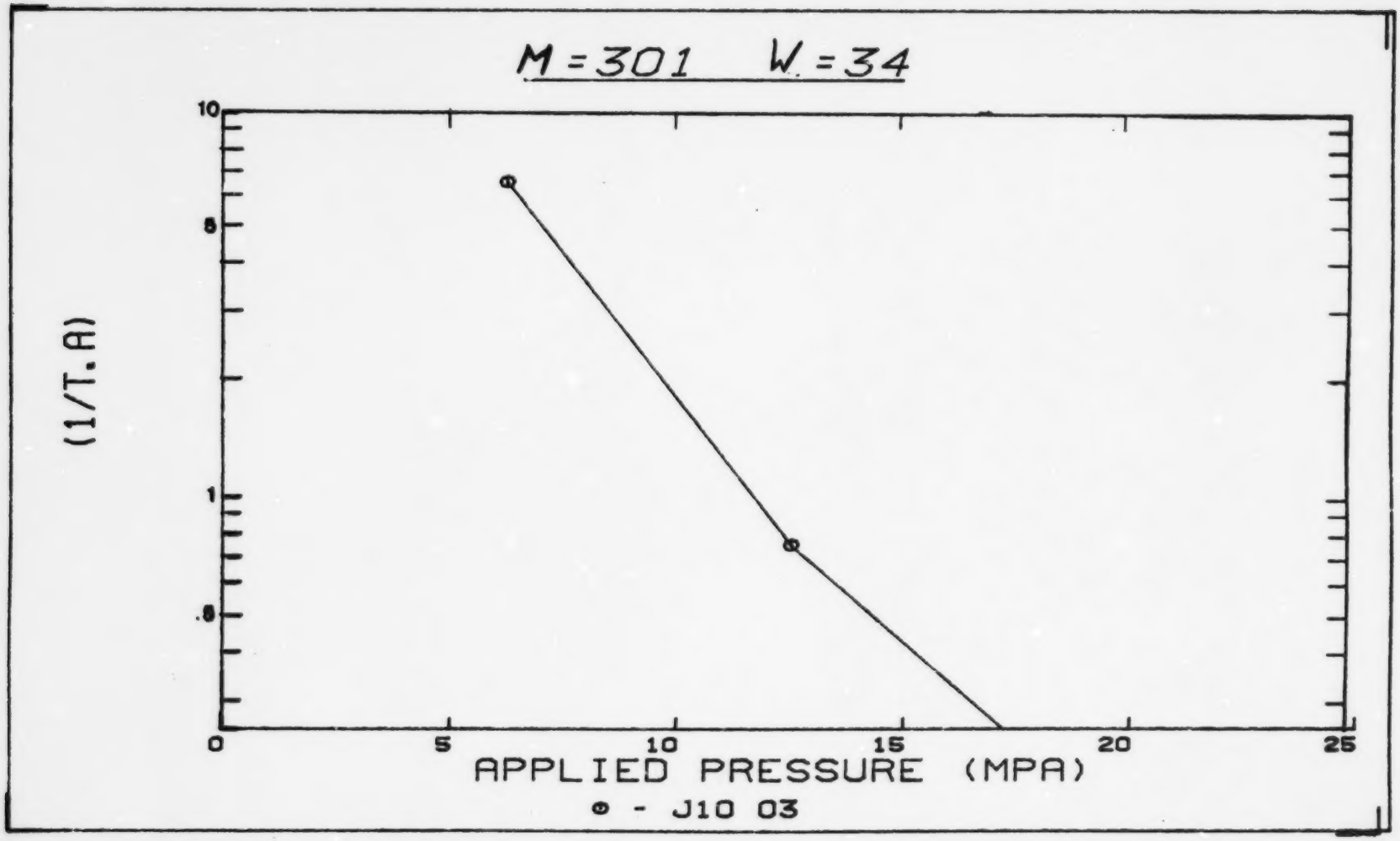
PARTICLE SIZE 56·25–6·35 mm

J10 2A +



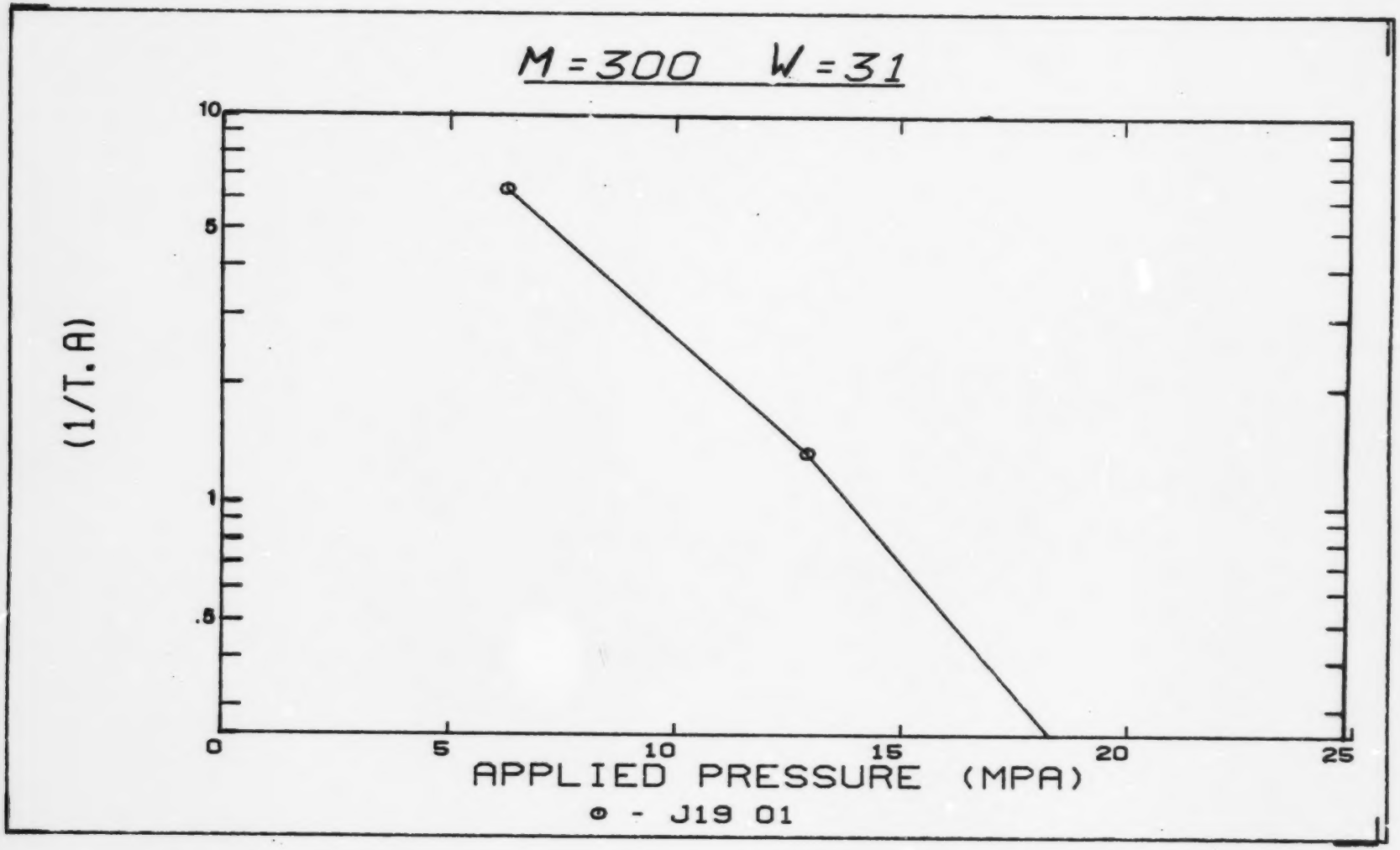
TUBE DIAMETER 880 mm

PARTICLE SIZE < 6·35 mm



TUBE DIAMETER 880 mm

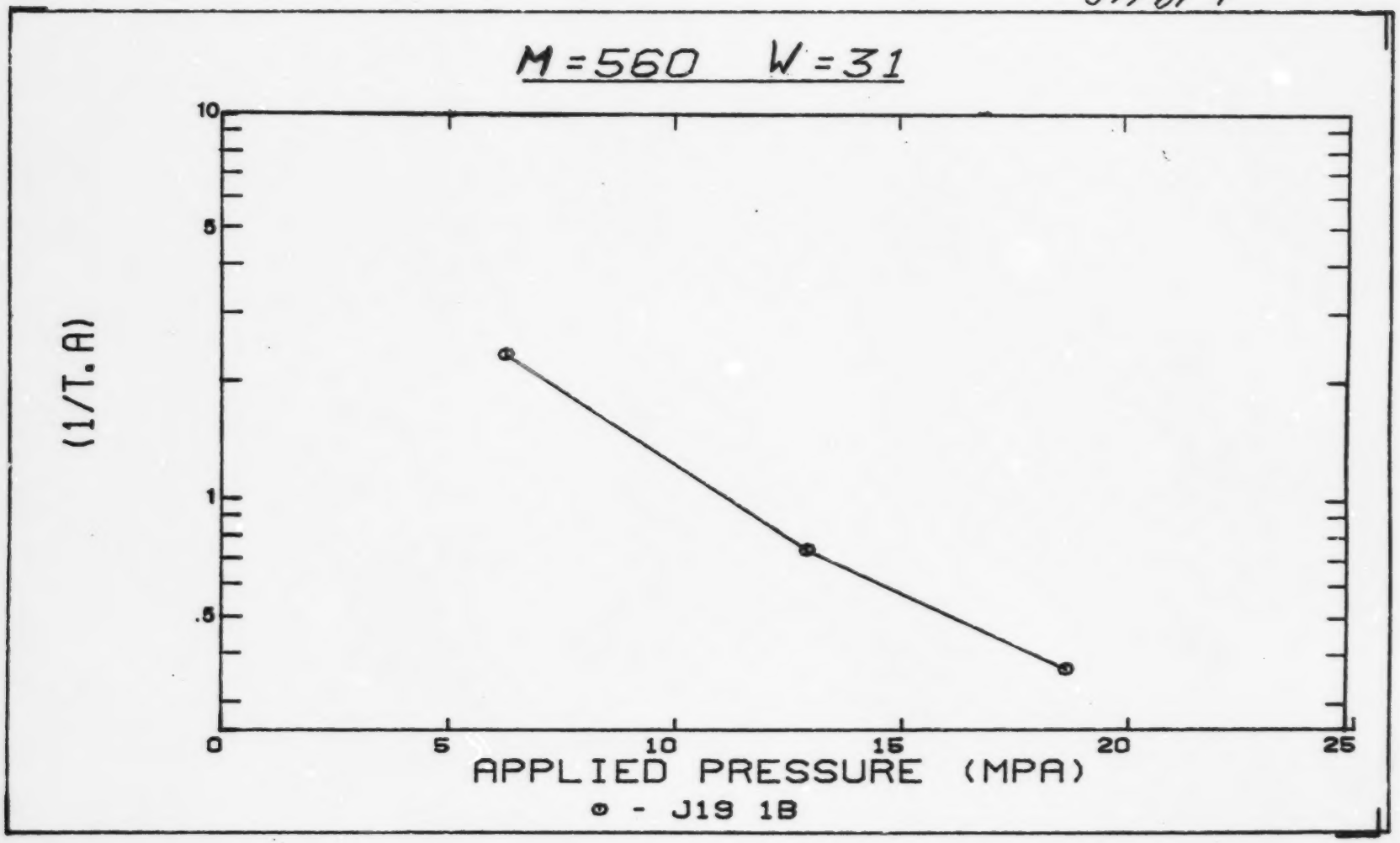
PARTICLE SIZE < 6-35



TUBE DIAMETER 880mm

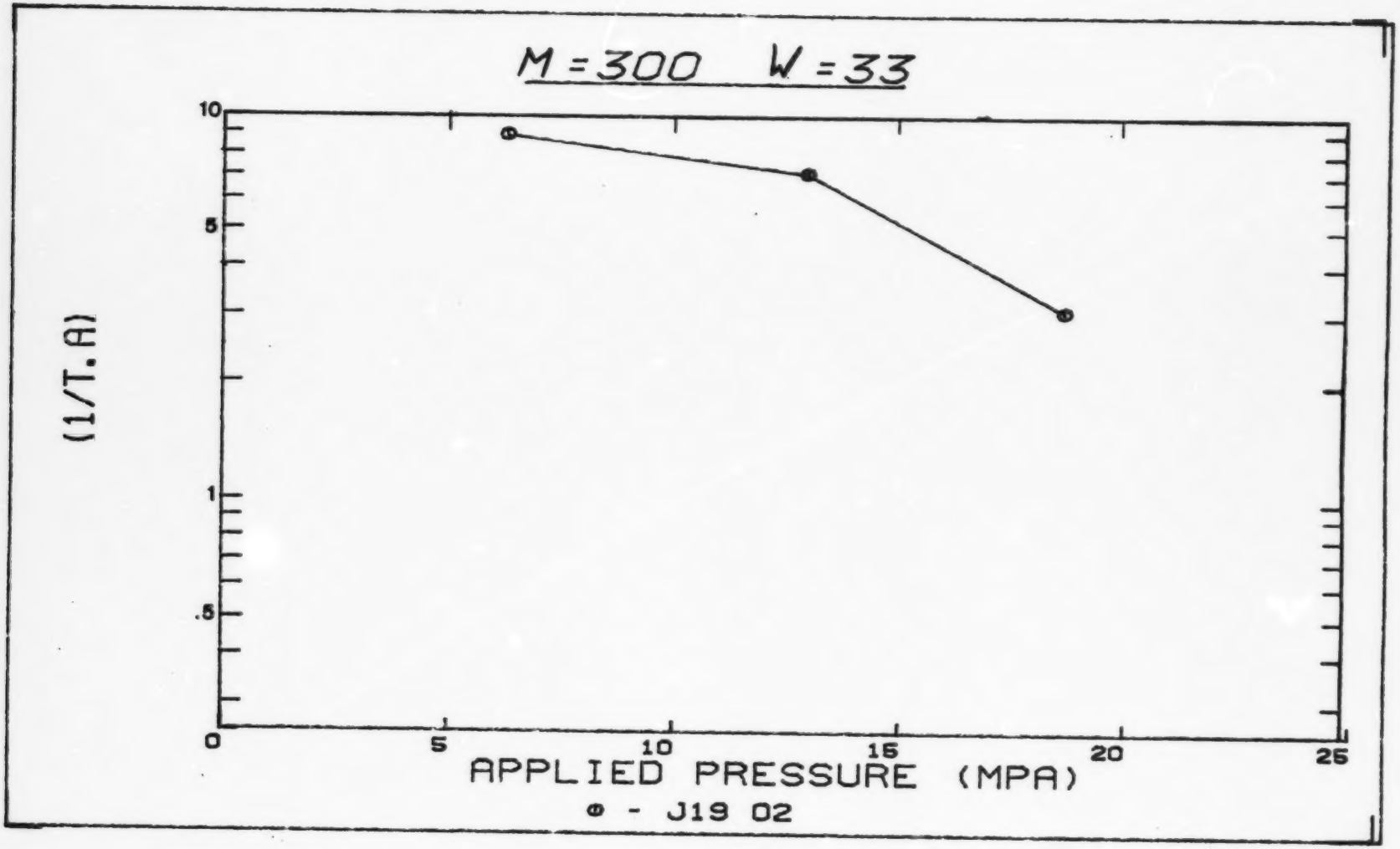
PARTICLE SIZE < 6-35 mm

J1901 +



TUBE DIAMETER 880mm

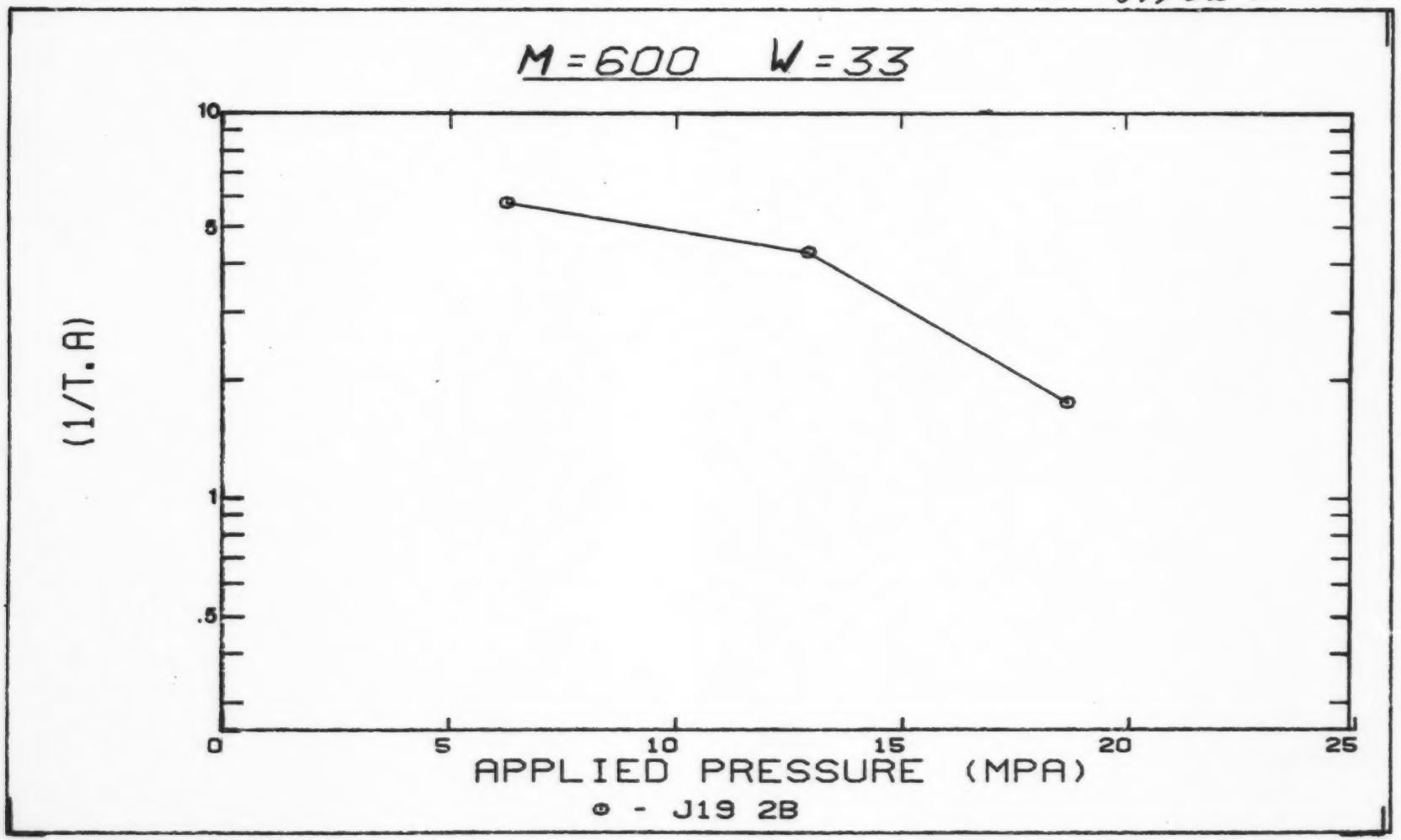
PARTICLE SIZE 56·25 – 4·76mm



TUBE DIAMETER 880mm

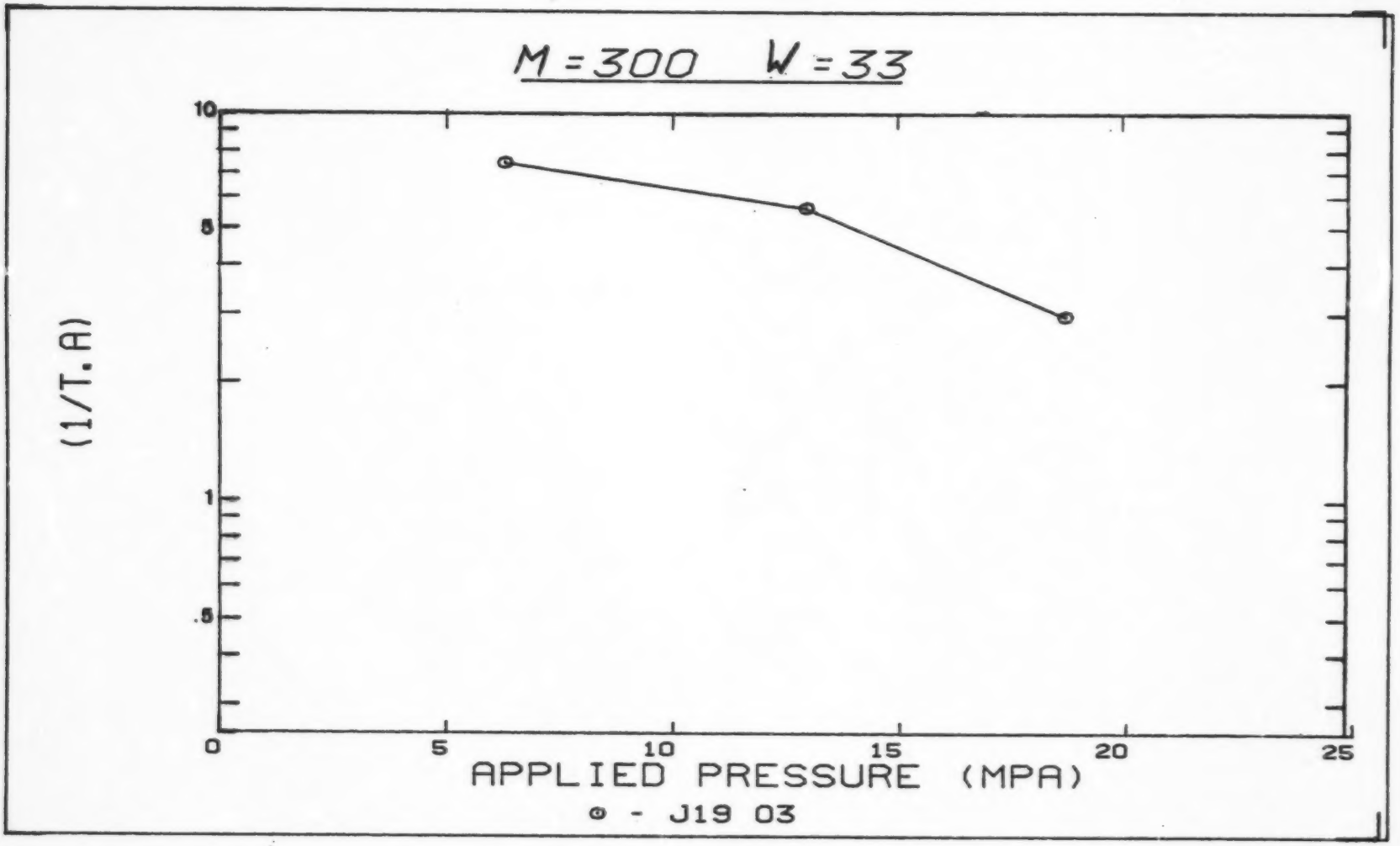
PARTICLE SIZE 56·25 – 4·76 mm

J1902 +



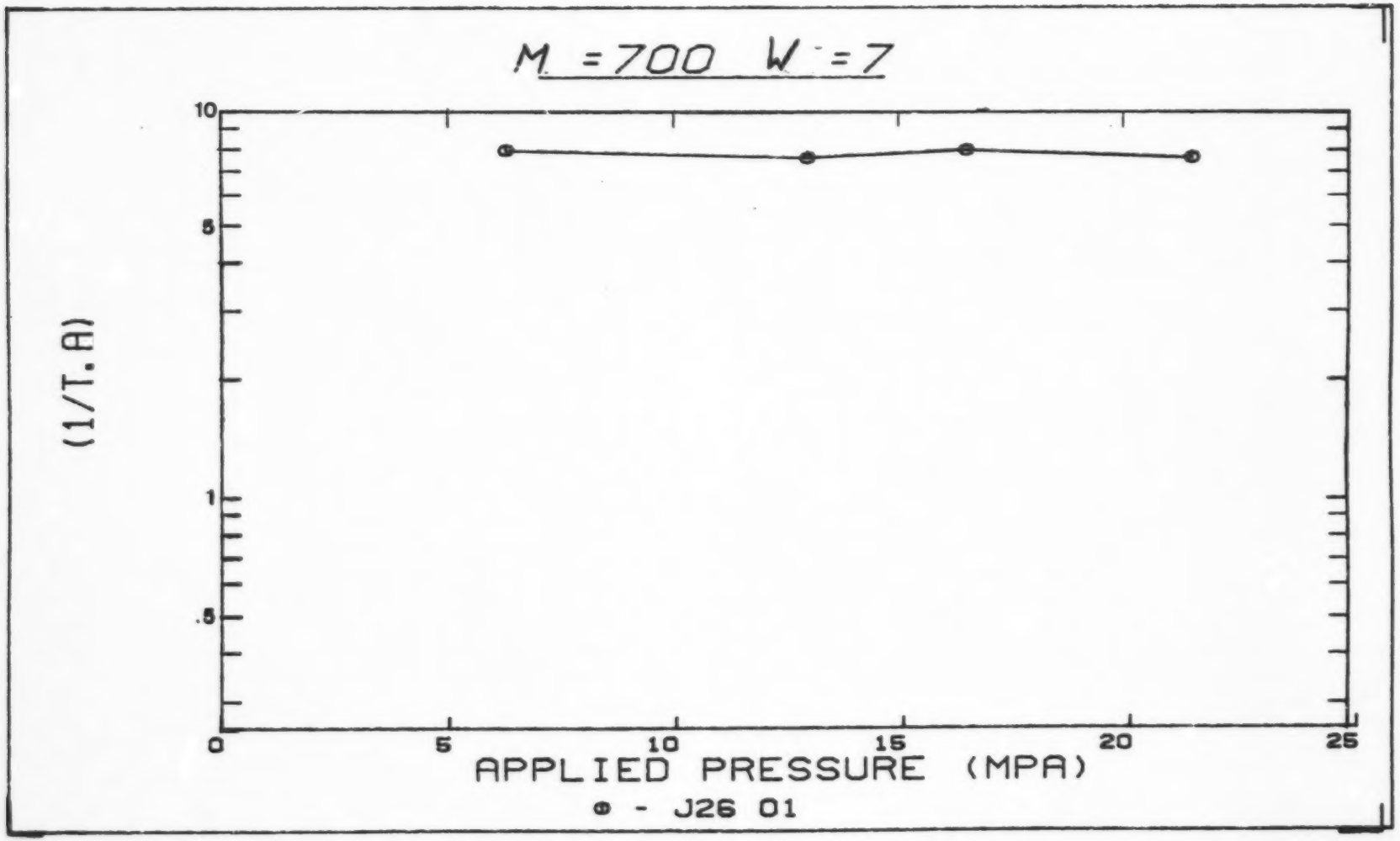
TUBE DIAMETER 880 mm

PARTICLE SIZE MIXED



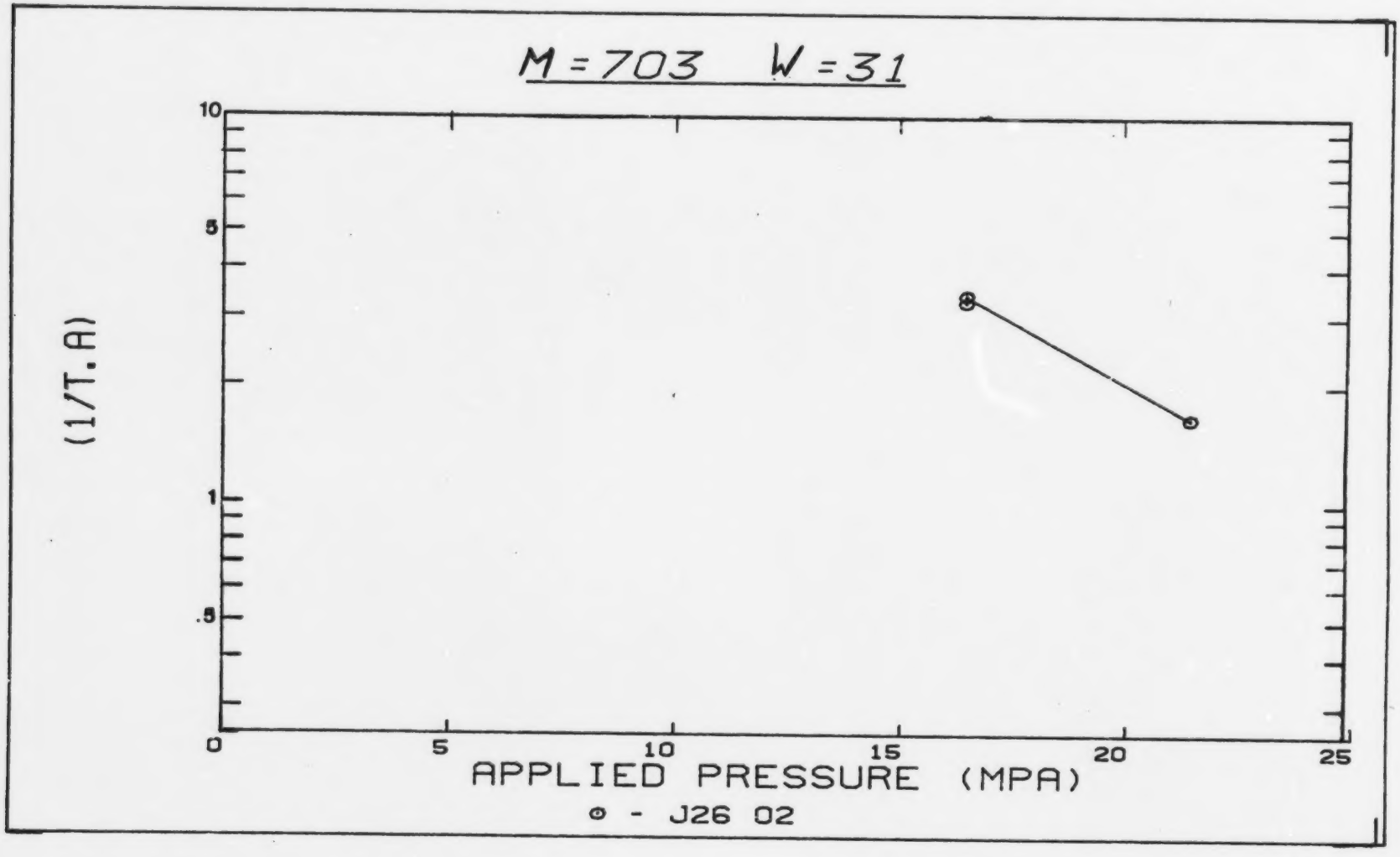
TUBE DIAMETER 500mm

PARTICLE SIZE > 56·25 mm



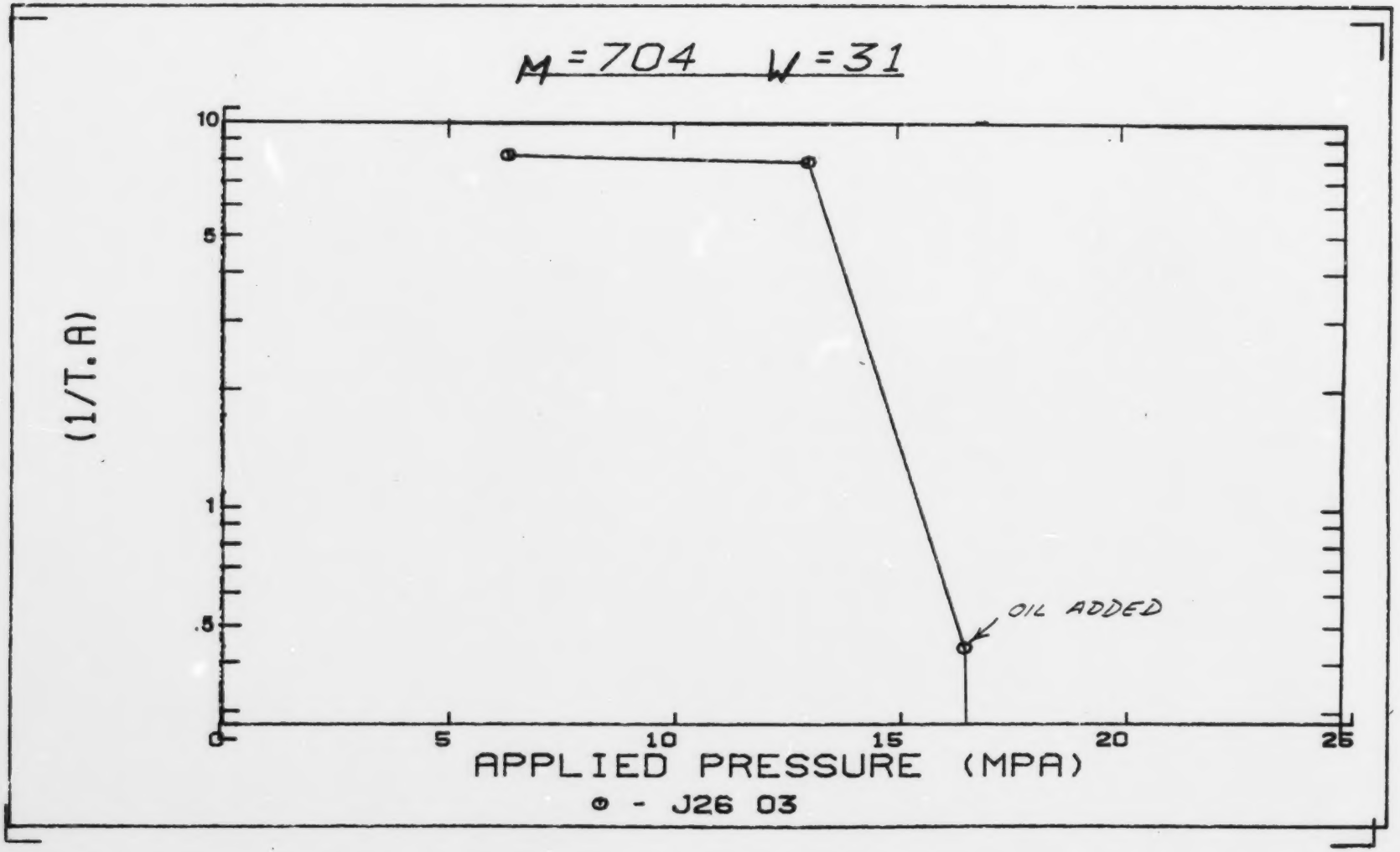
TUBE DIAMETER 500mm

PARTICLE SIZE AS RECEIVED



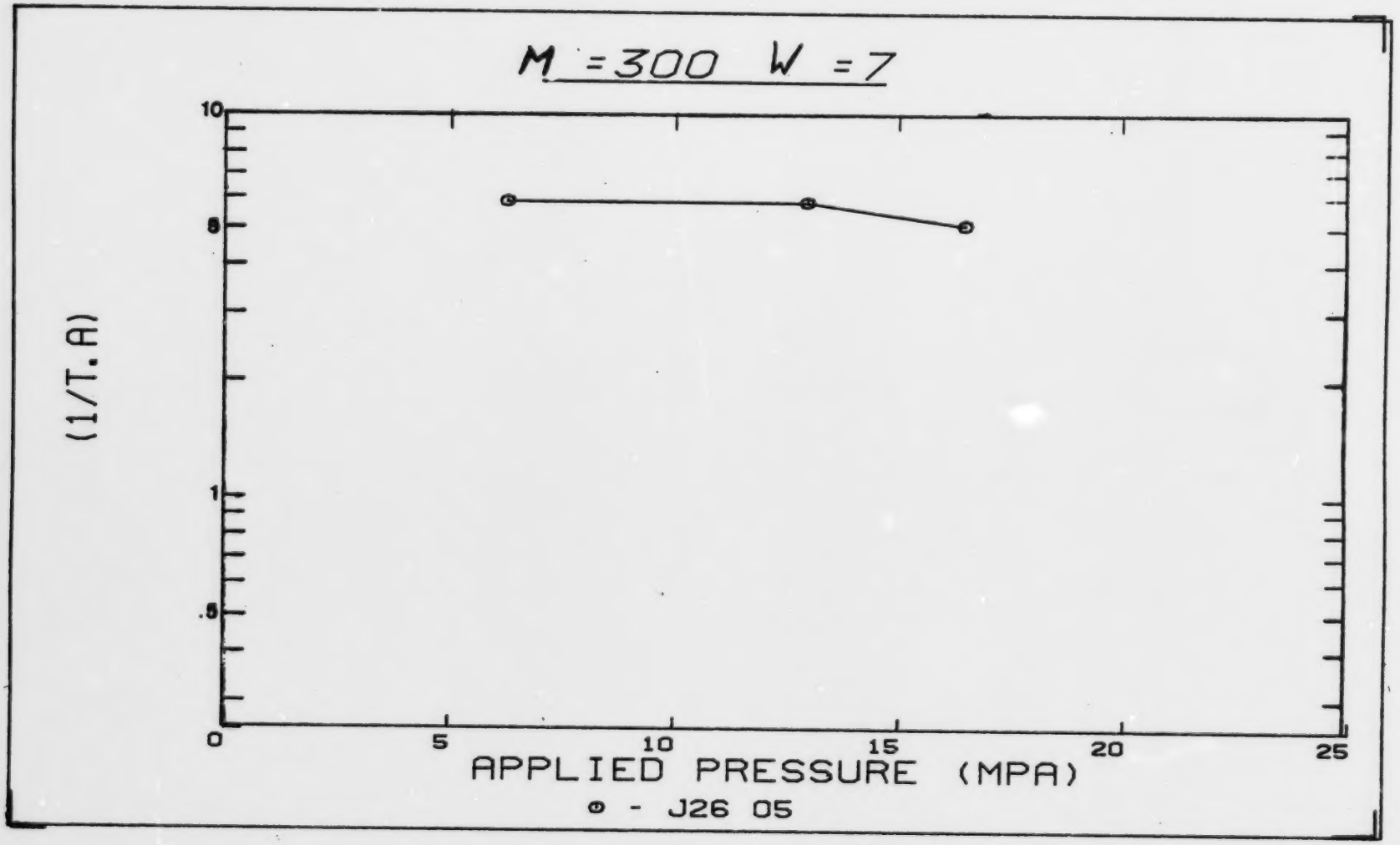
TUBE DIAMETER 50 mm

PARTICLE SIZE AS RECEIVED



TUBE DIAMETER 500 mm

PARTICLE SIZE < 4.76 mm

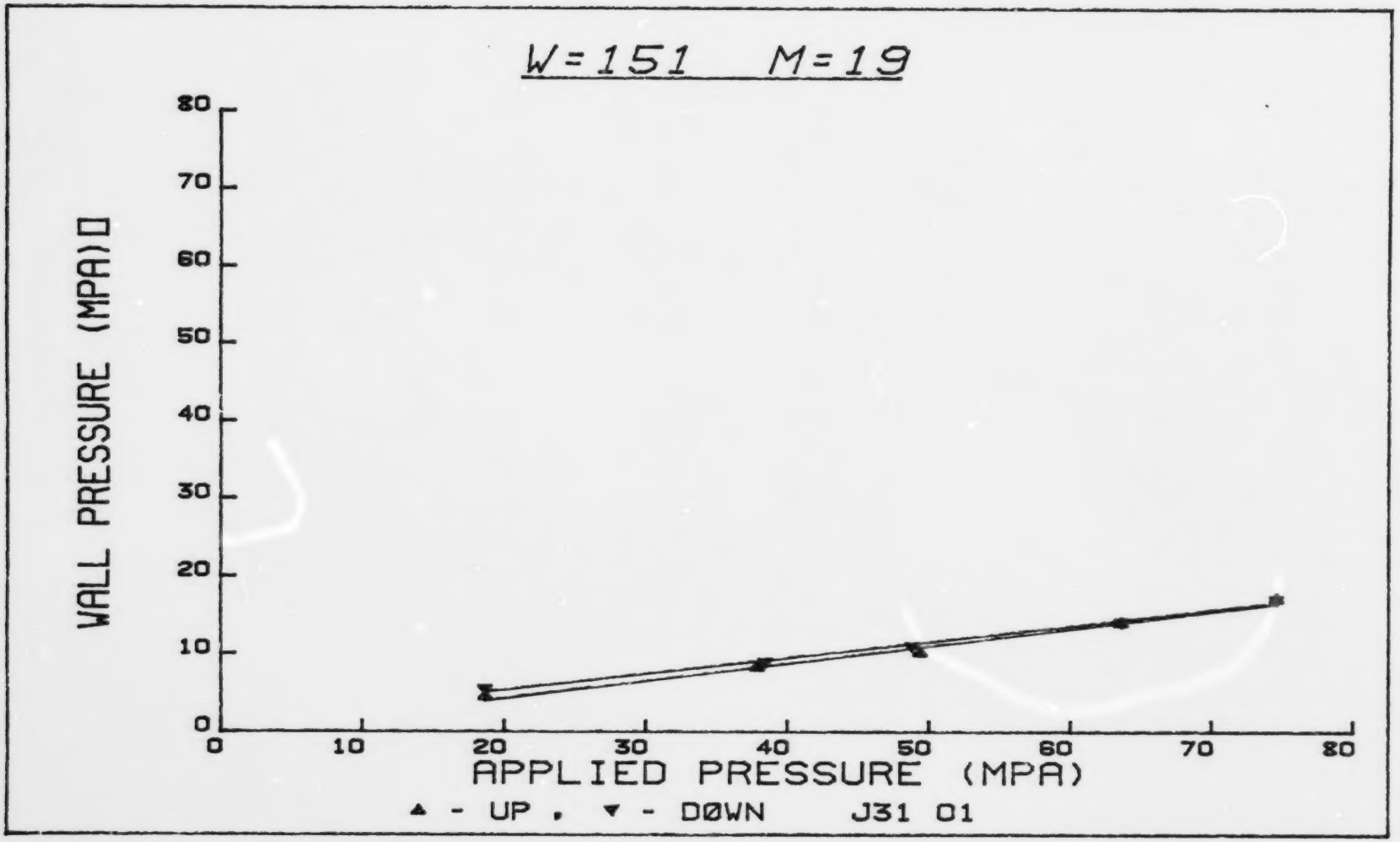


WALL PRESSURE VS APPLIED PRESSURE

500 mm TUBE

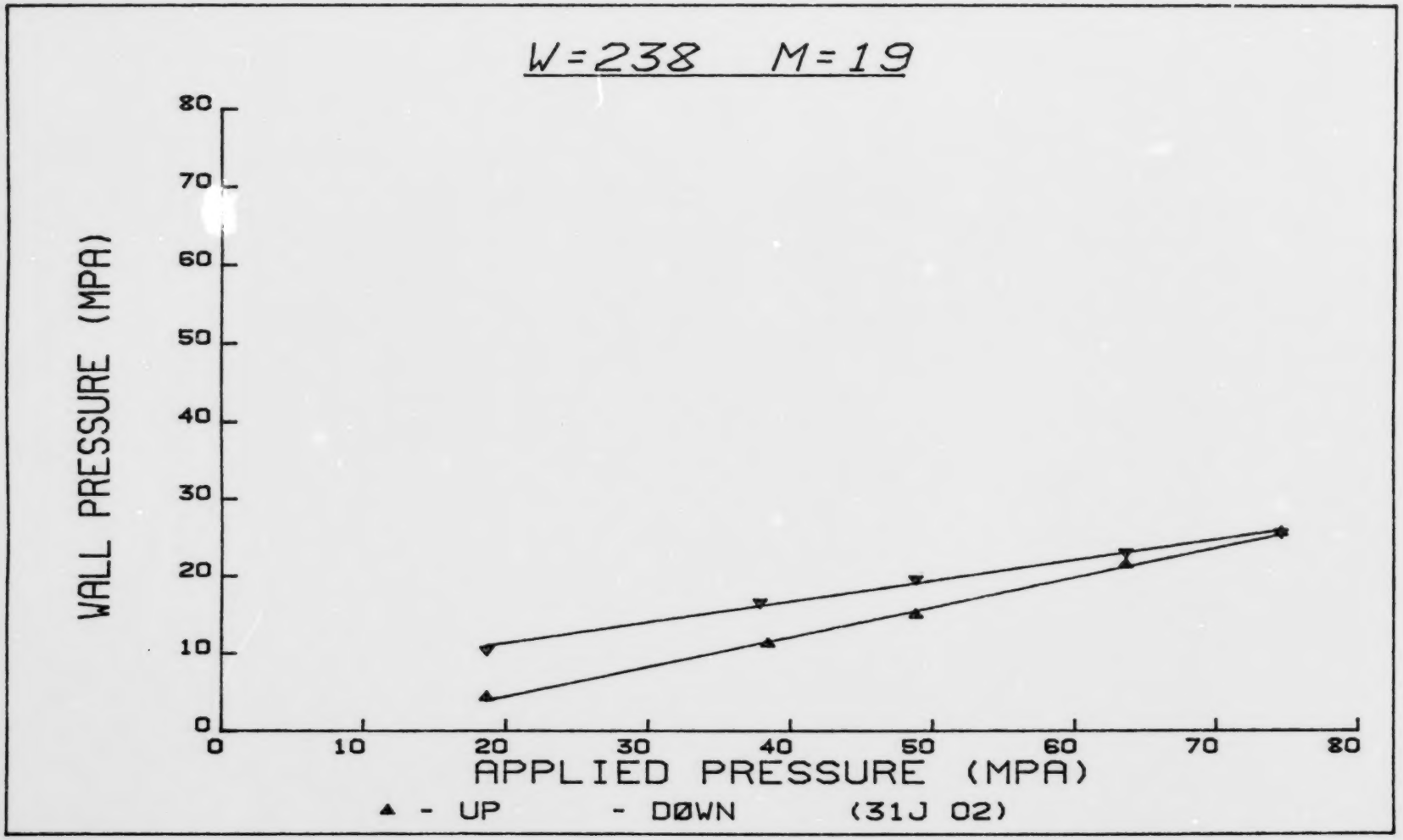
UP $P_W = -0.218 + 0.225\ P_a$

DOWN $P_W = 1.222 + 0.208\ P_a$



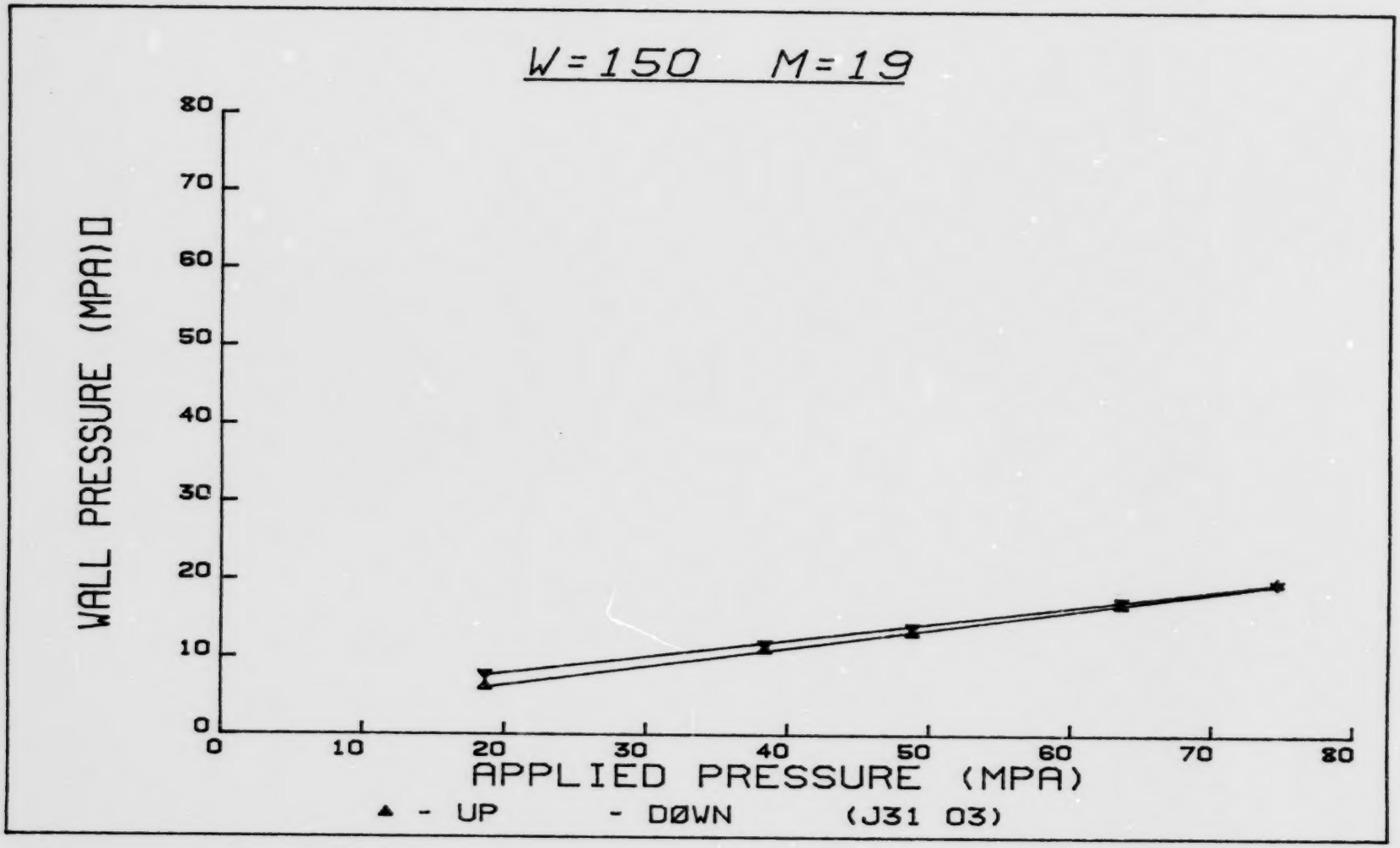
UP $P_w = -3.210 + 0.384\ P_a$

DOWN $P_w = 6.020 + 0.268\ P_a$



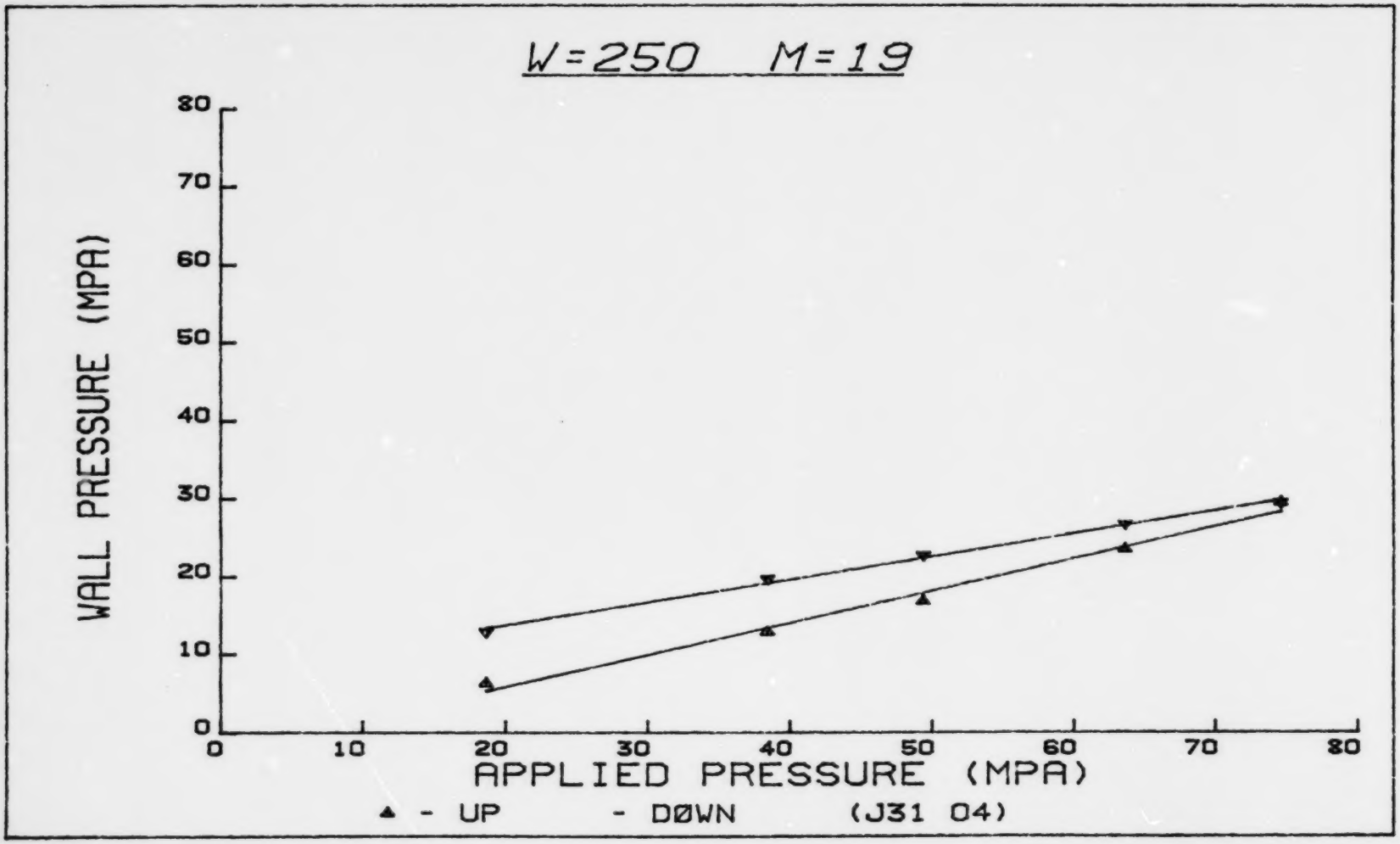
UP $P_w = 1.656 + .240\ P_a$

DOWN $P_w = 3.710 + .214\ P_a$



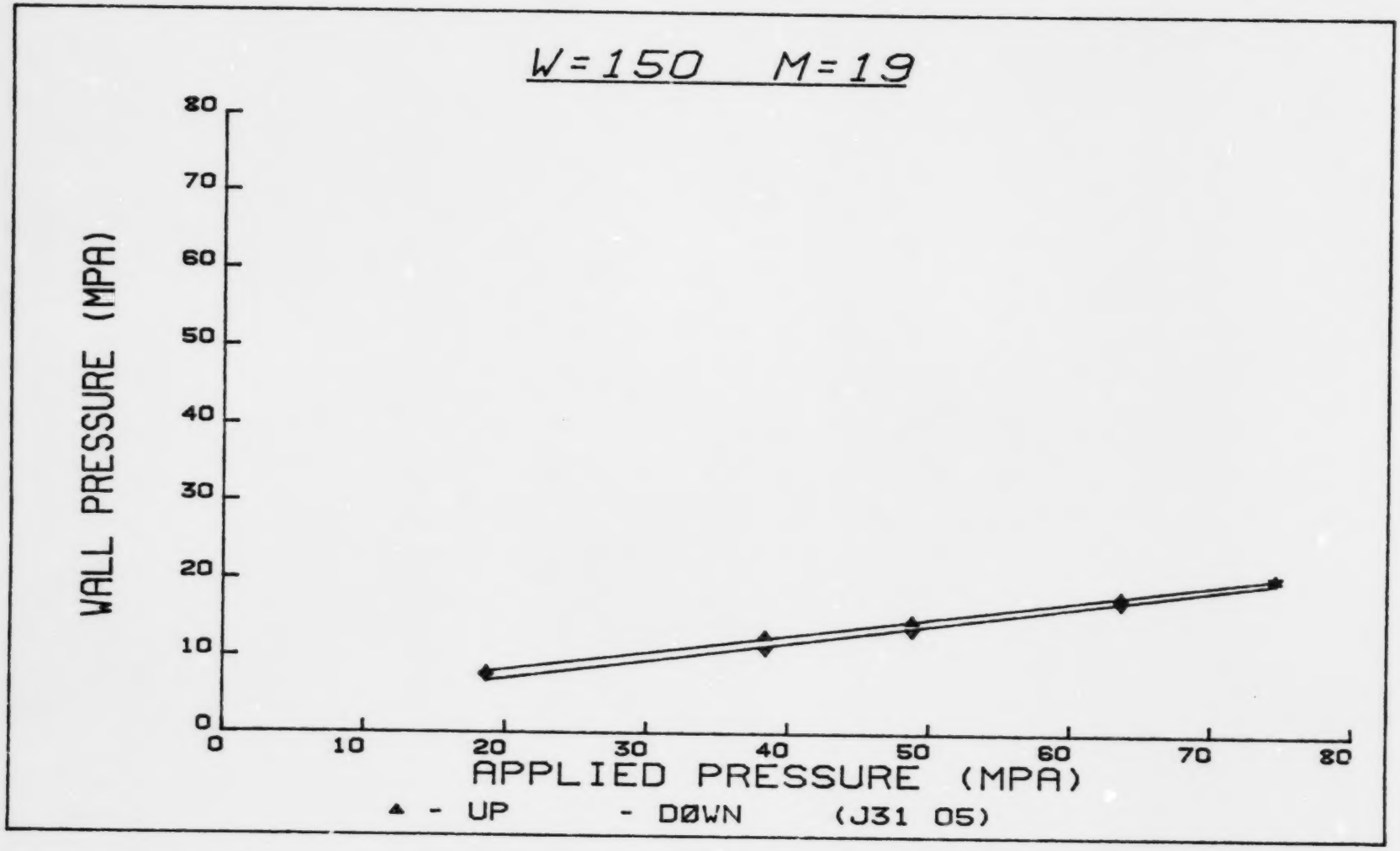
UP $P_w = -2.361 + 0.412\ P_a$

DOWN $P_w = 7.884 + 0.295\ P_a$



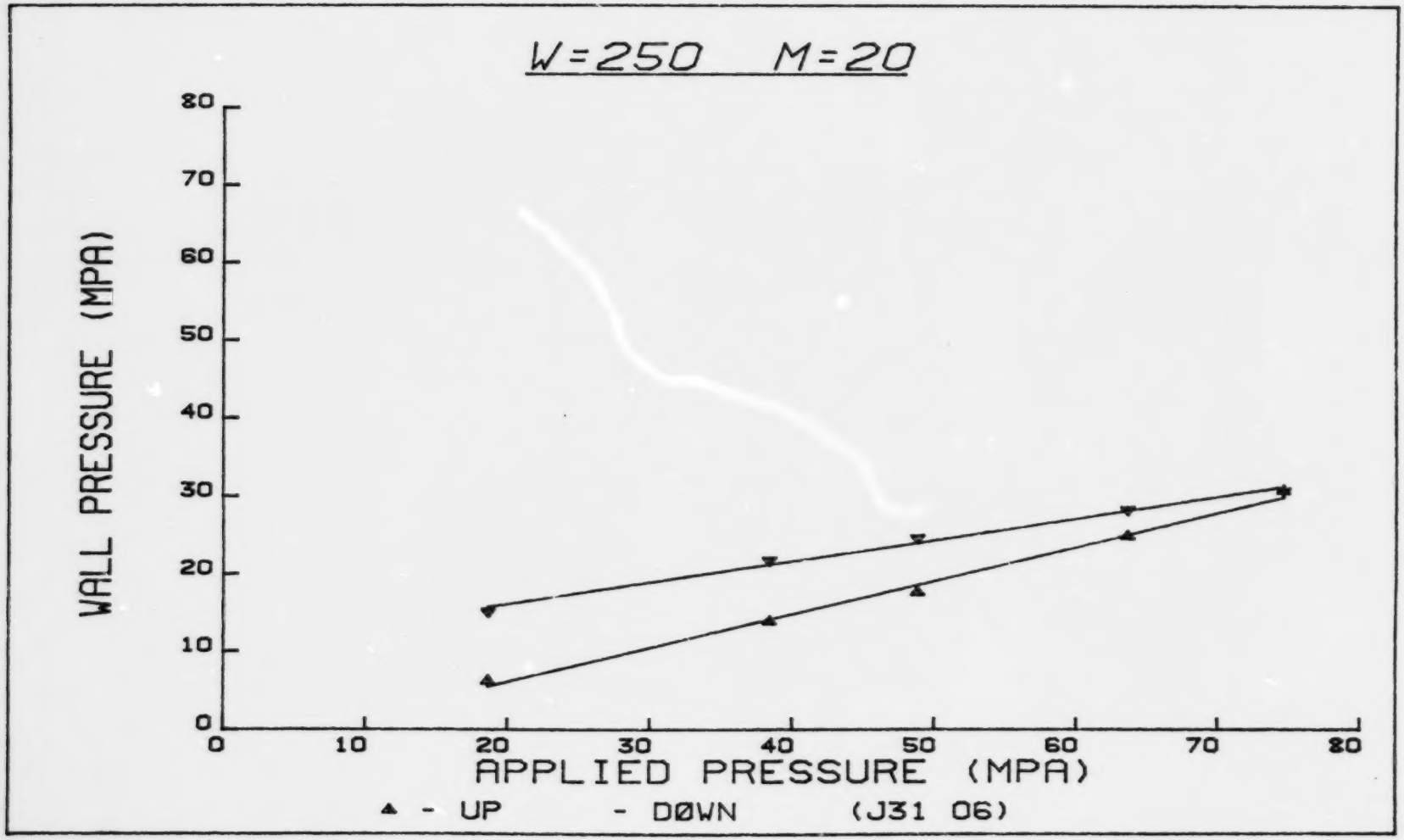
UP $P_W = 3.832 + 0.224\ P_a$

DOWN $P_W = 2.472 + 0.234\ P_a$



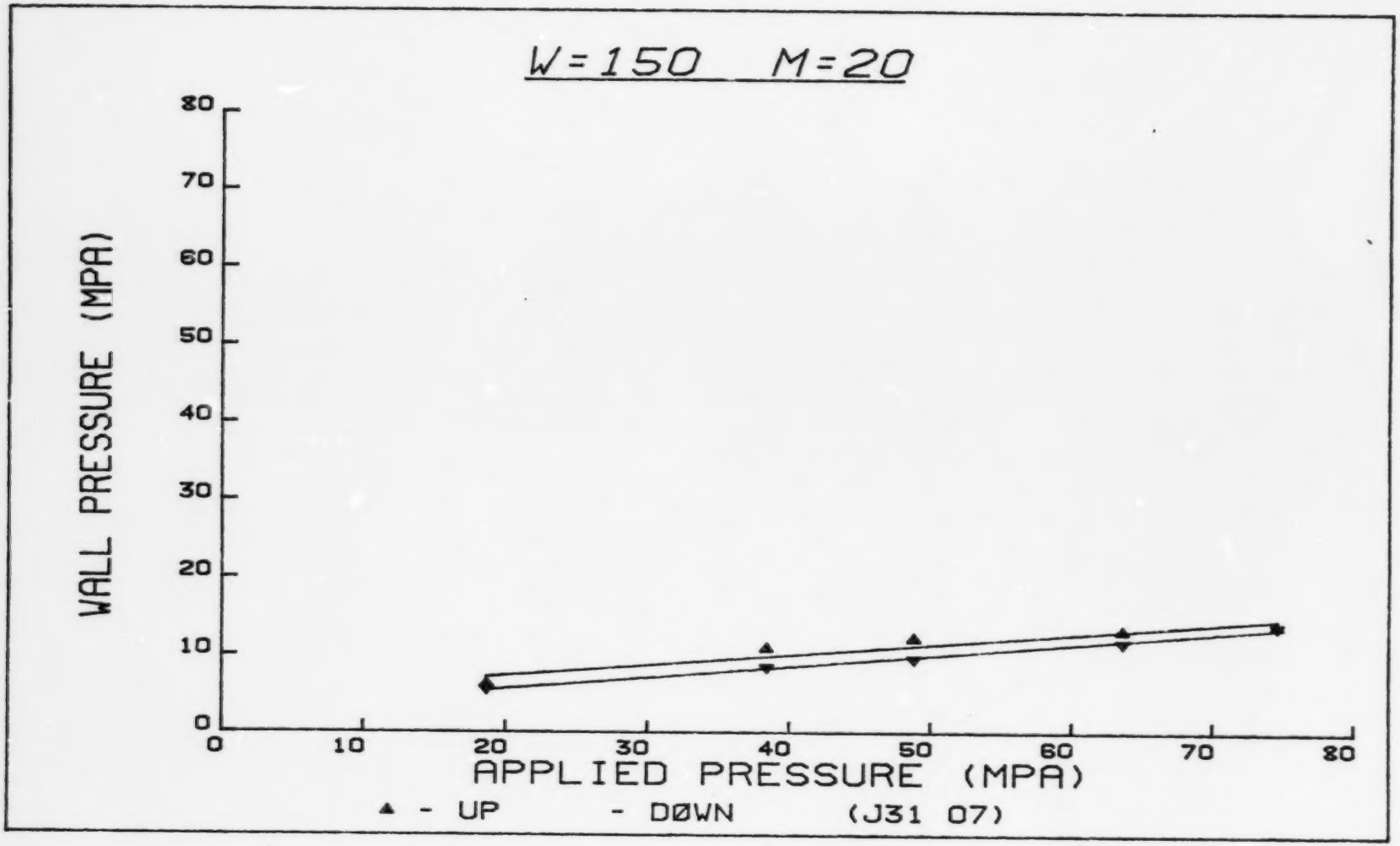
UP $P_w = -2.618 + 0.436\, P_a$

DOWN $P_w = 10.576 + 0.277\, P_a$



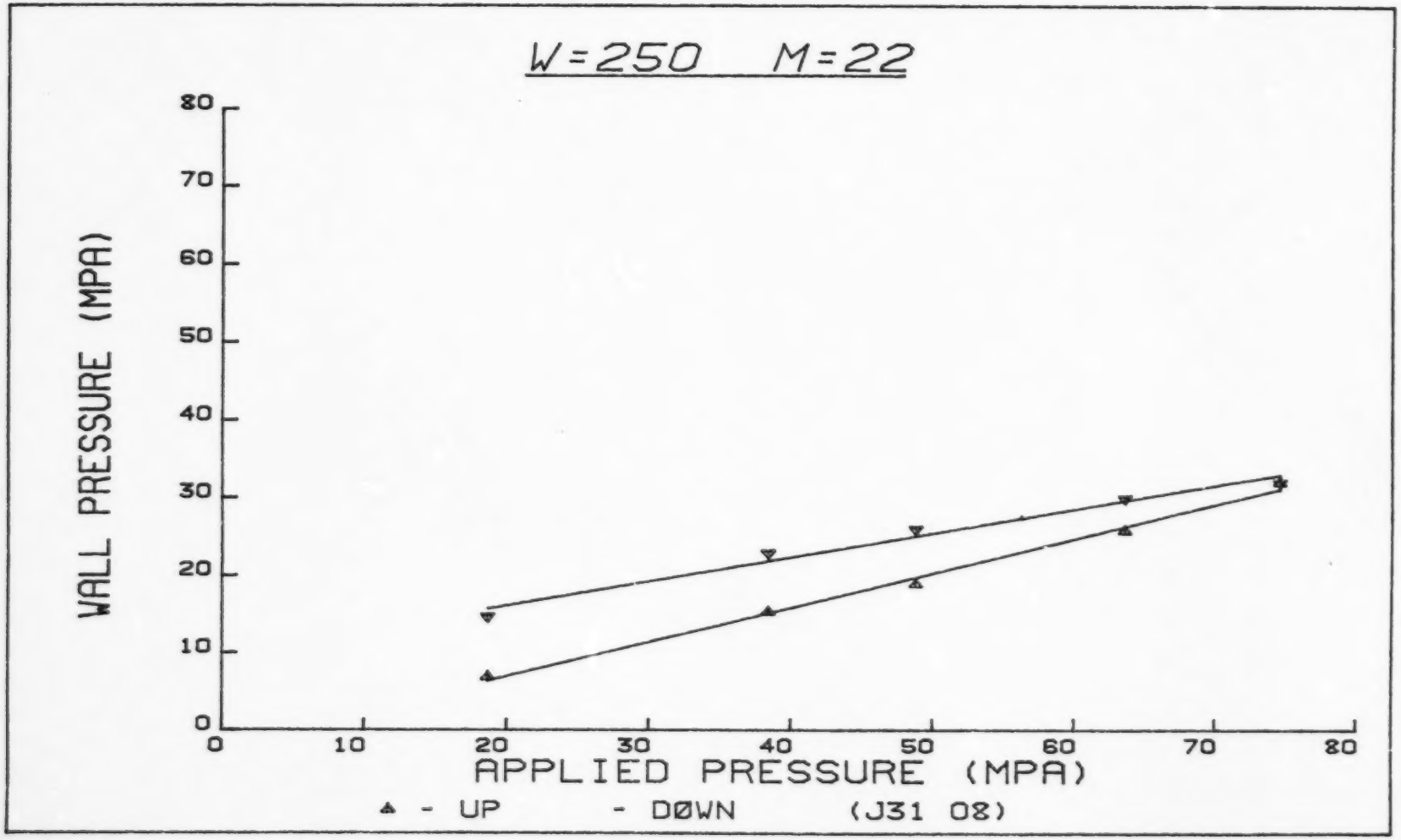
UP $P_W = 4.738 + 0.134\,P_a$

DOWN $P_W = 2.828 + 0.992\,P_a$



UP $P_W = -1.873 + 0.443\ P_a$

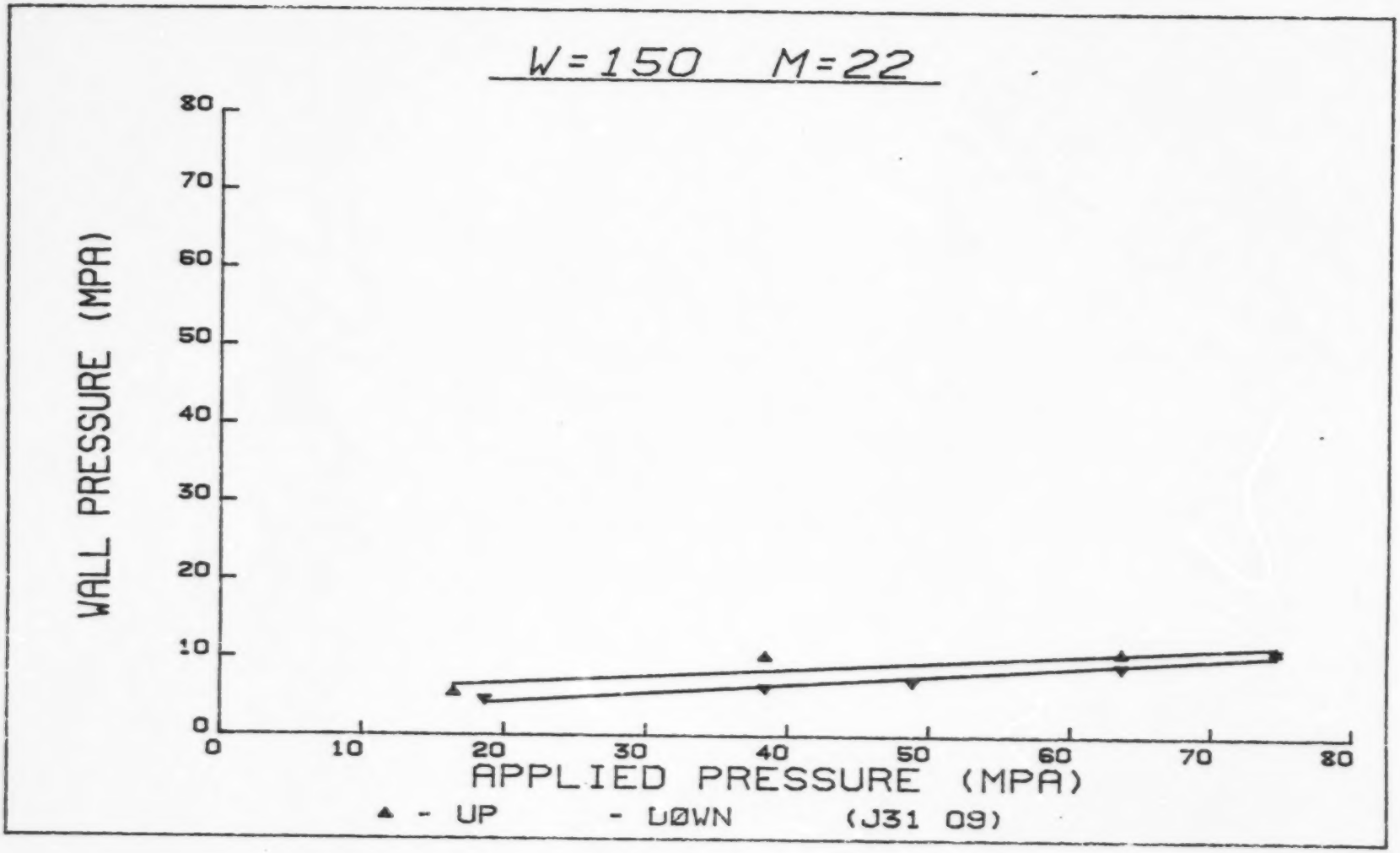
DOWN $P_W = 9.965 + 0.310\ P_a$



UP $P_W = 4.923 + 0.091\ P_a$

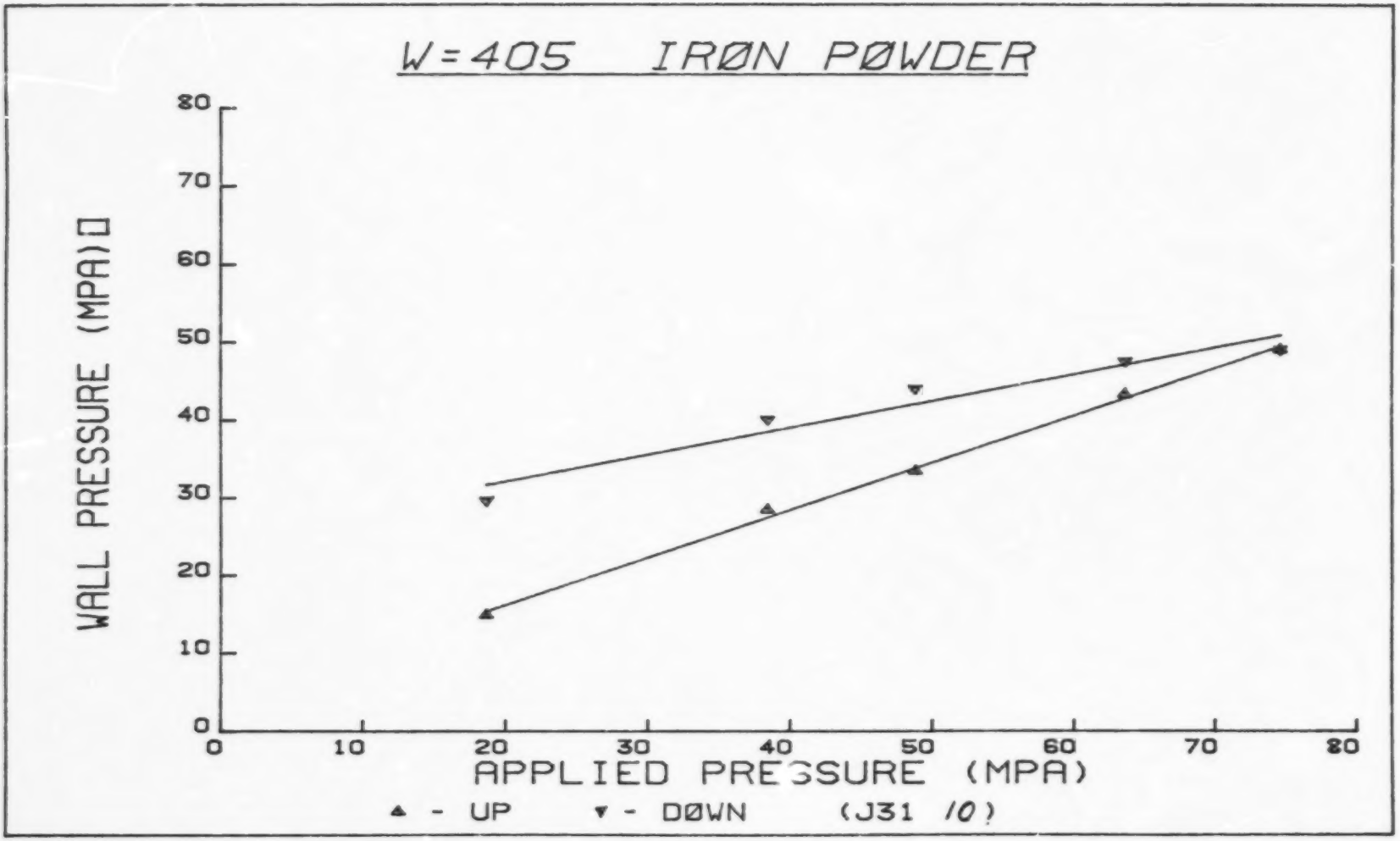
DOWN $P_W = 2.065 + 0.113\ P_a$

see next sheet



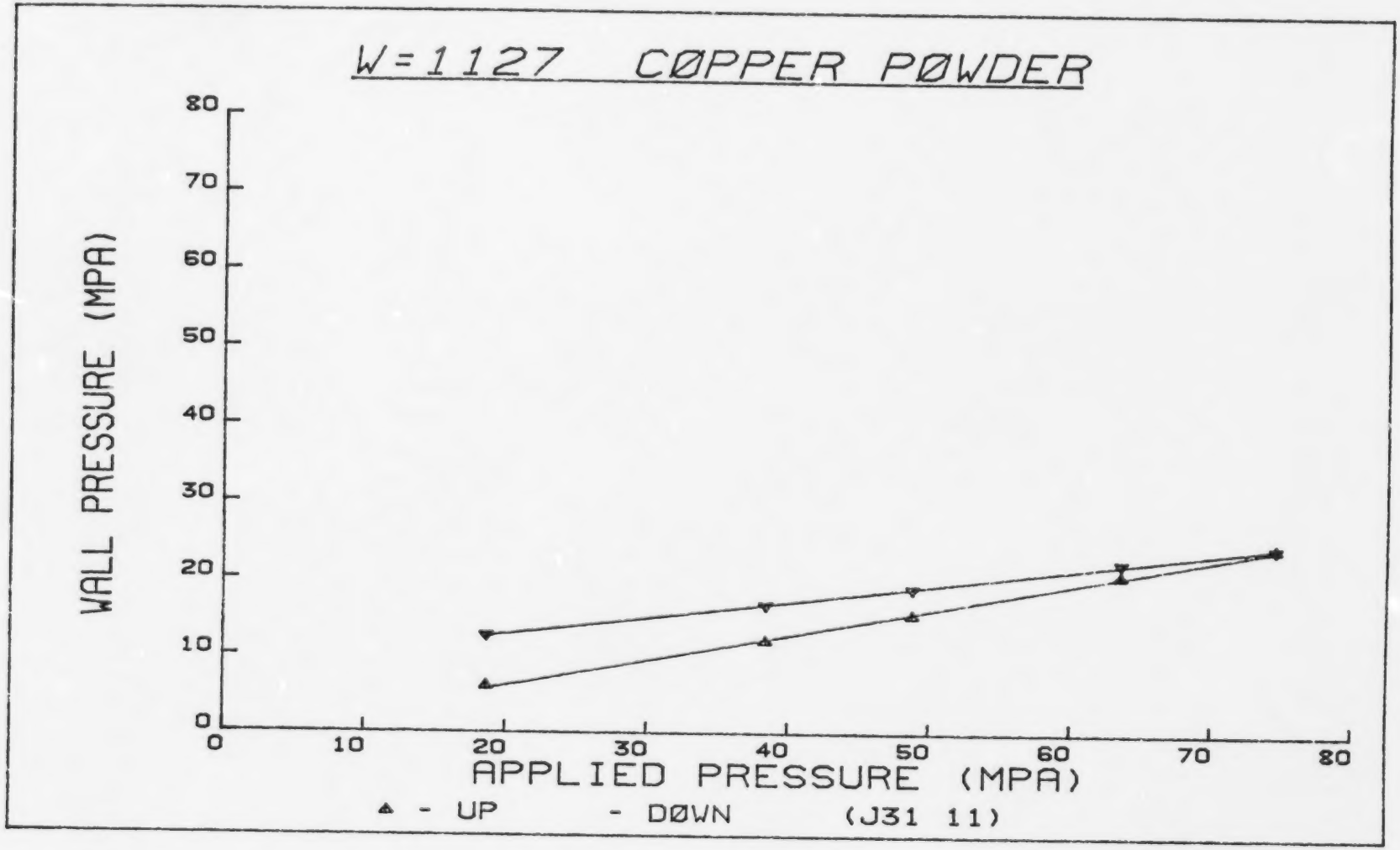
UP $P_W = 4.120 + 0.607\ P_a$

DOWN $P_W = 25.272 + 0.343\ P_a$



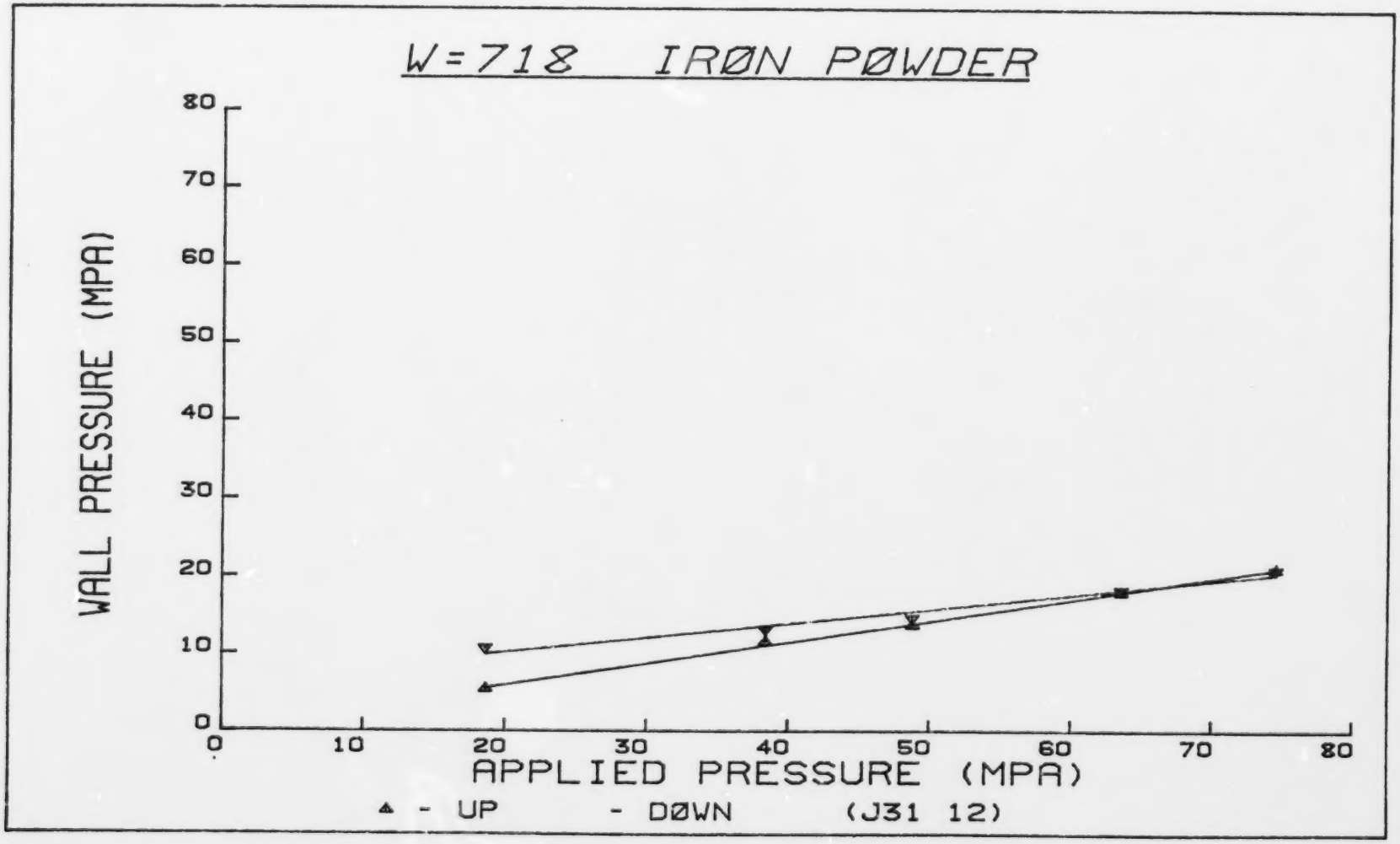
UP $P_w = -0.520 + 0.331\ P_a$

DOWN $P_w = 8.543 + 0.213\ P_a$



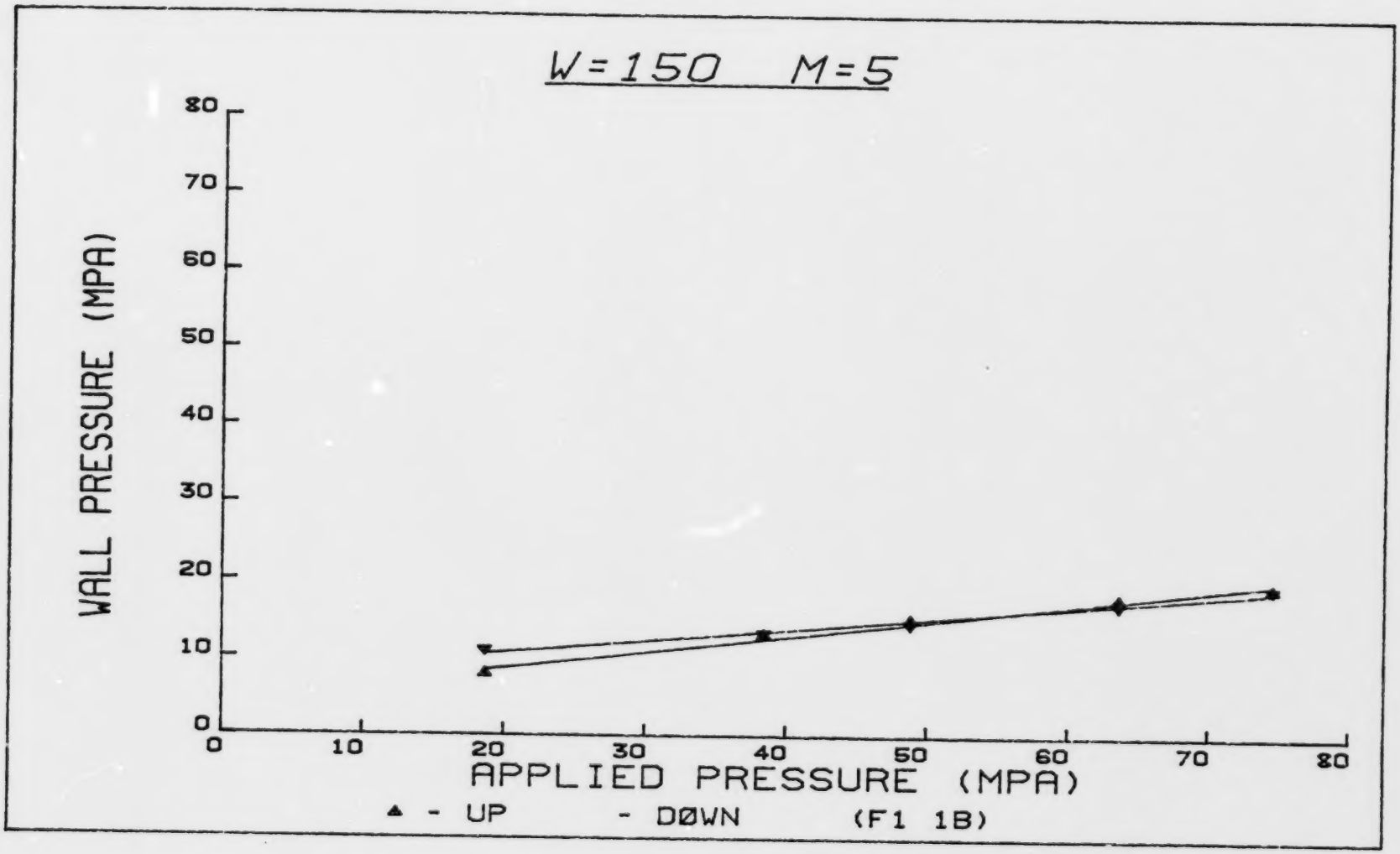
UP $P_W = 0.406 + 0.277\ P_a$

DOWN $P_W = 6.526 + 0.186\ P_a$



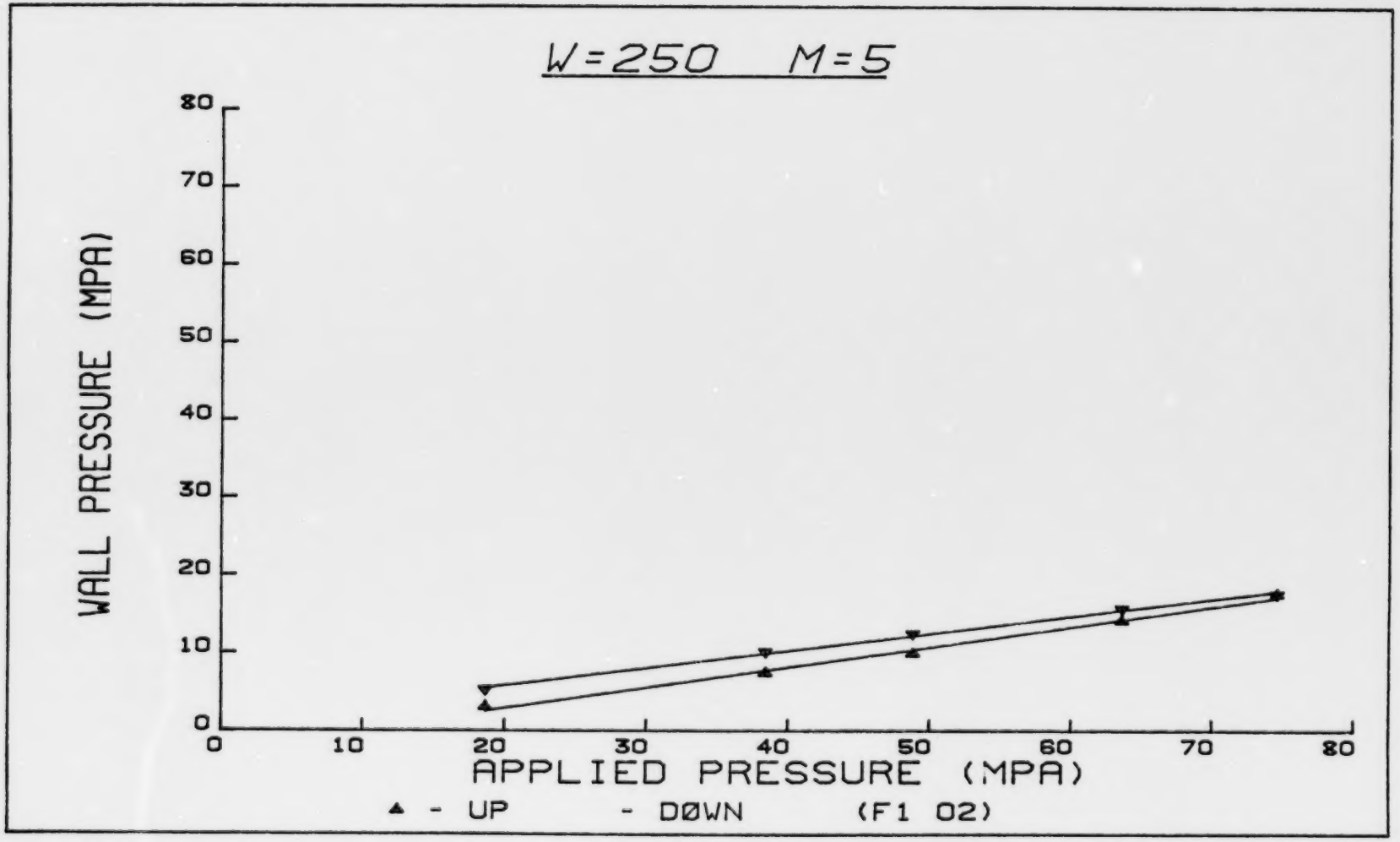
UP $P_w = 4.622 + 0.206\ P_a$

DOWN $P_w = 7.783 + 0.149\ P_a$



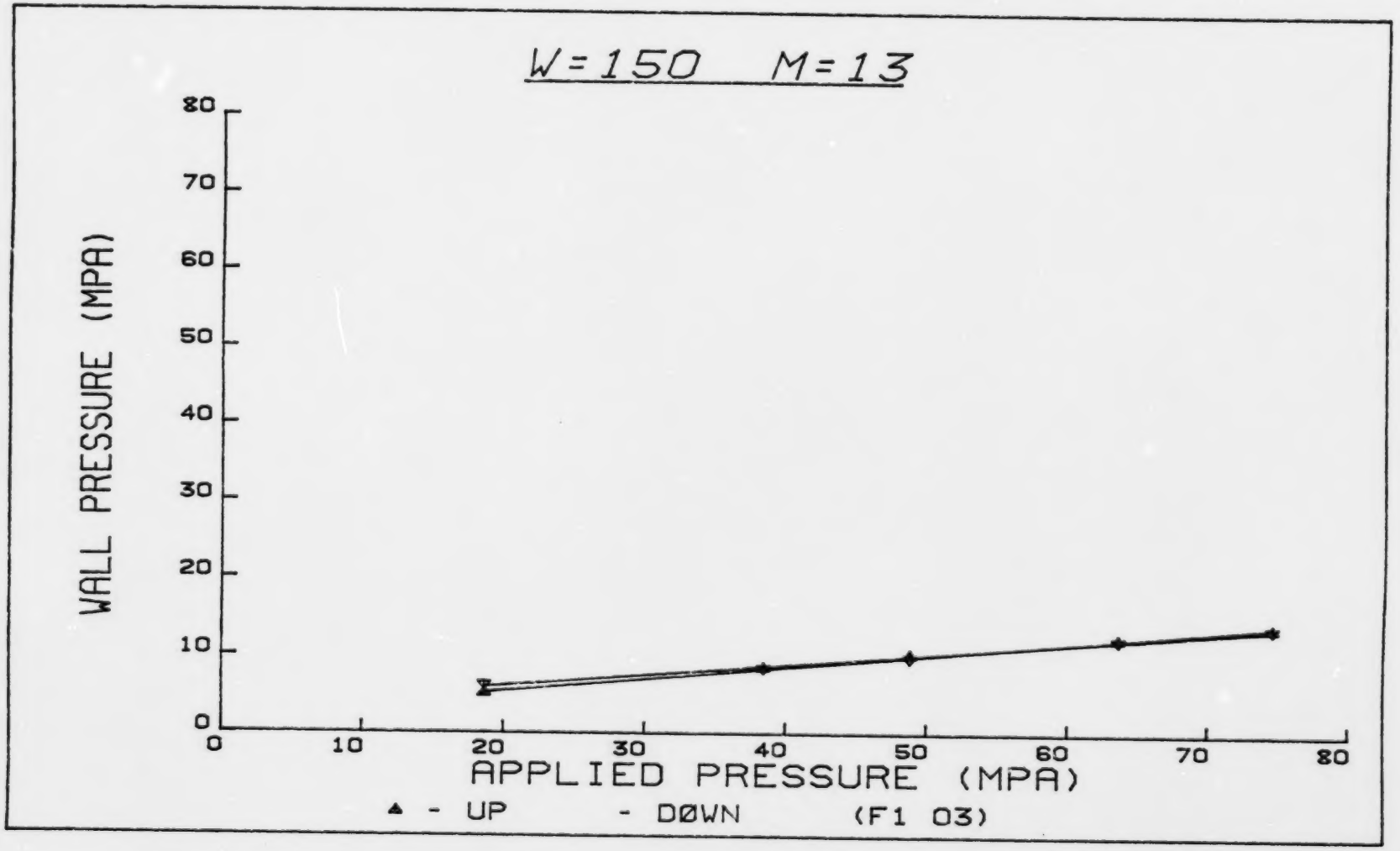
UP $P_W = -2.322 + 0.262\ P_a$

DOWN $P_W = 1.360 + 0.224\ P_a$



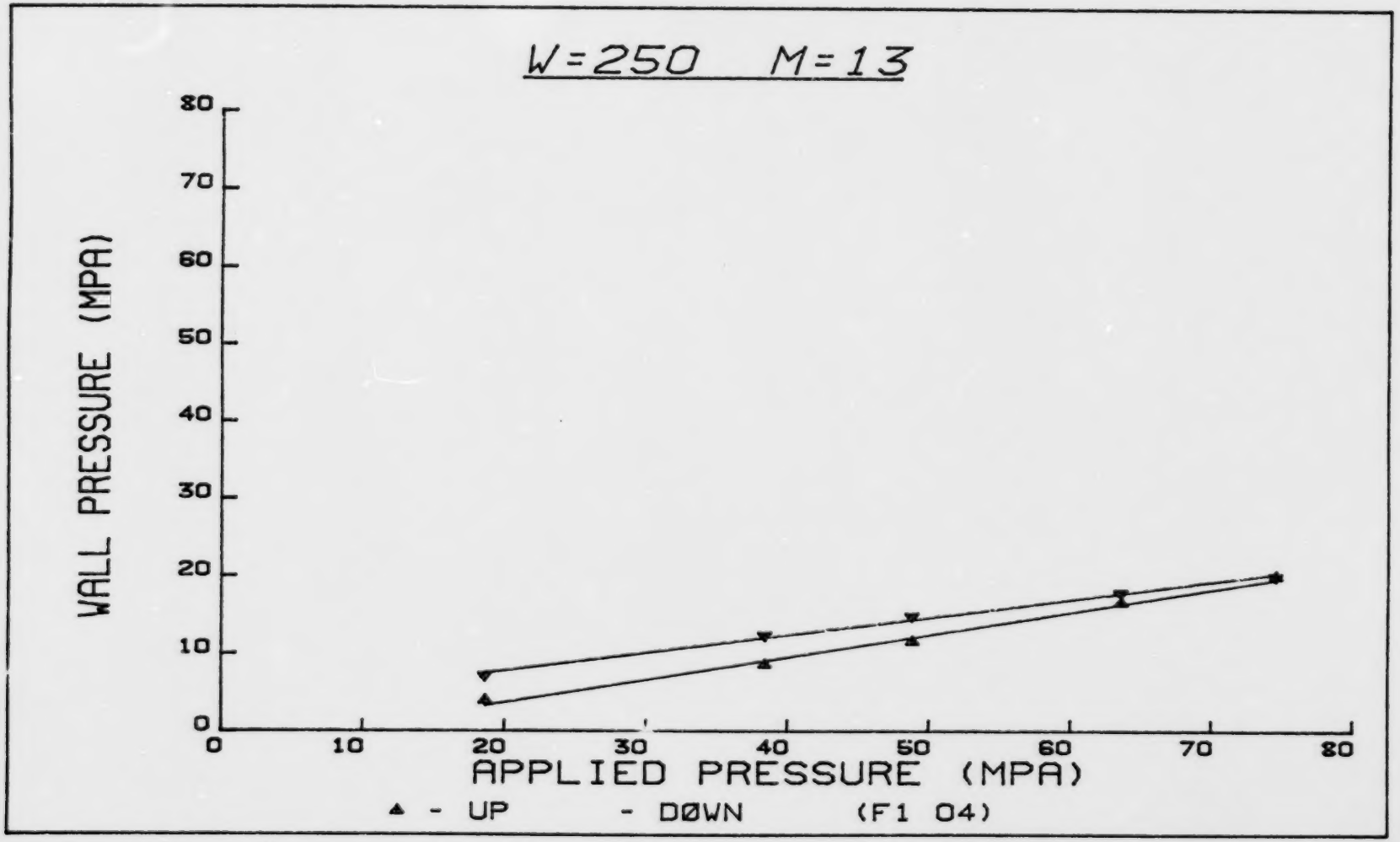
UP $P_w = 2.345 + 0.157\ P_a$

DOWN $P_w = 3.455 + 0.137\ P_a$



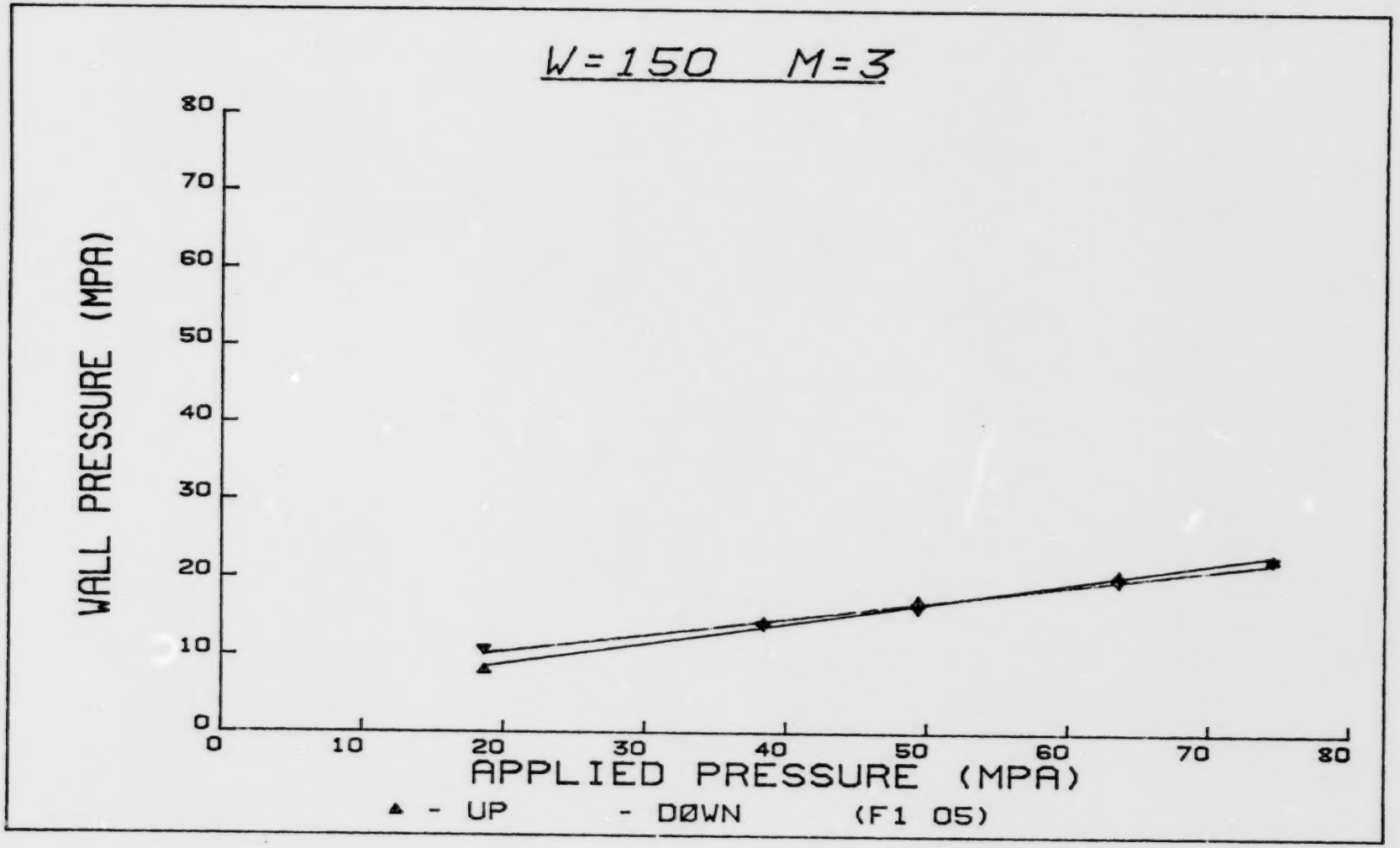
UP $P_w = -2.175 + 0.294\ P_a$

DOWN $P_w = 3.165 + 0.232\ P_a$



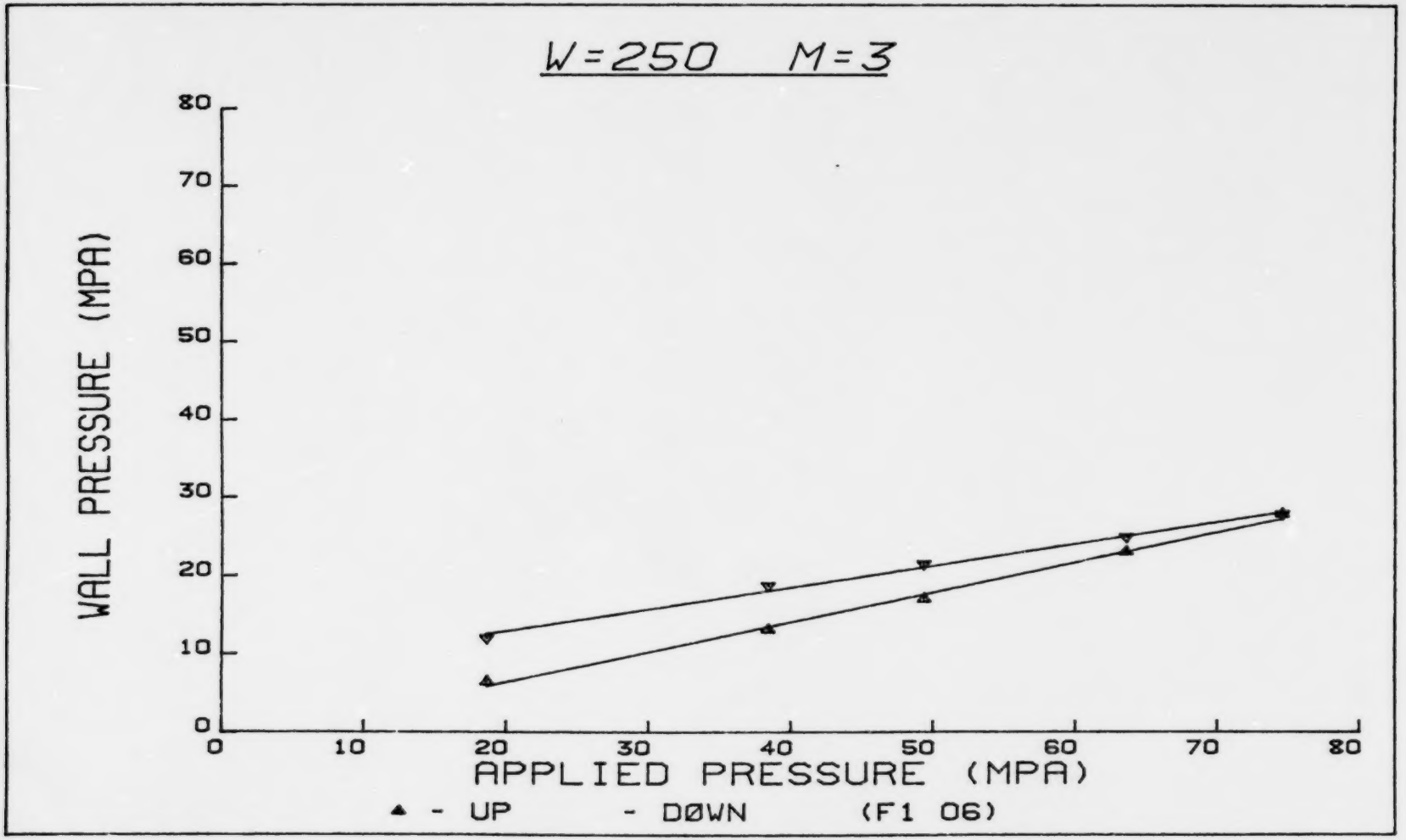
UP $P_w = 3.670 + 0.261\ P_a$

DOWN $P_w = 6.203 + 0.213\ P_a$



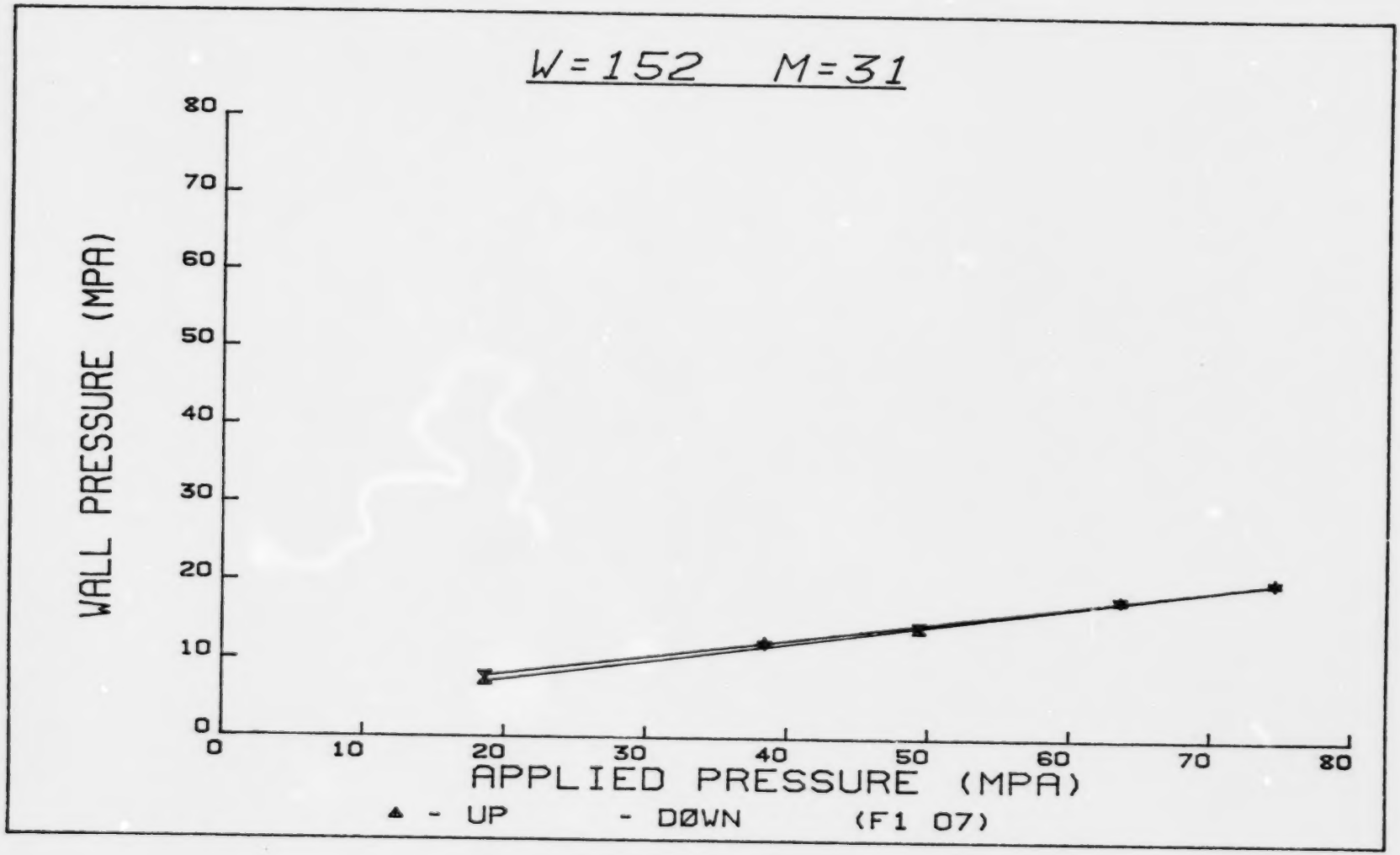
UP $P_W = -1.213 + 0.382\ P_a$

DOWN $P_W = 7.352 + 0.278\ P_a$



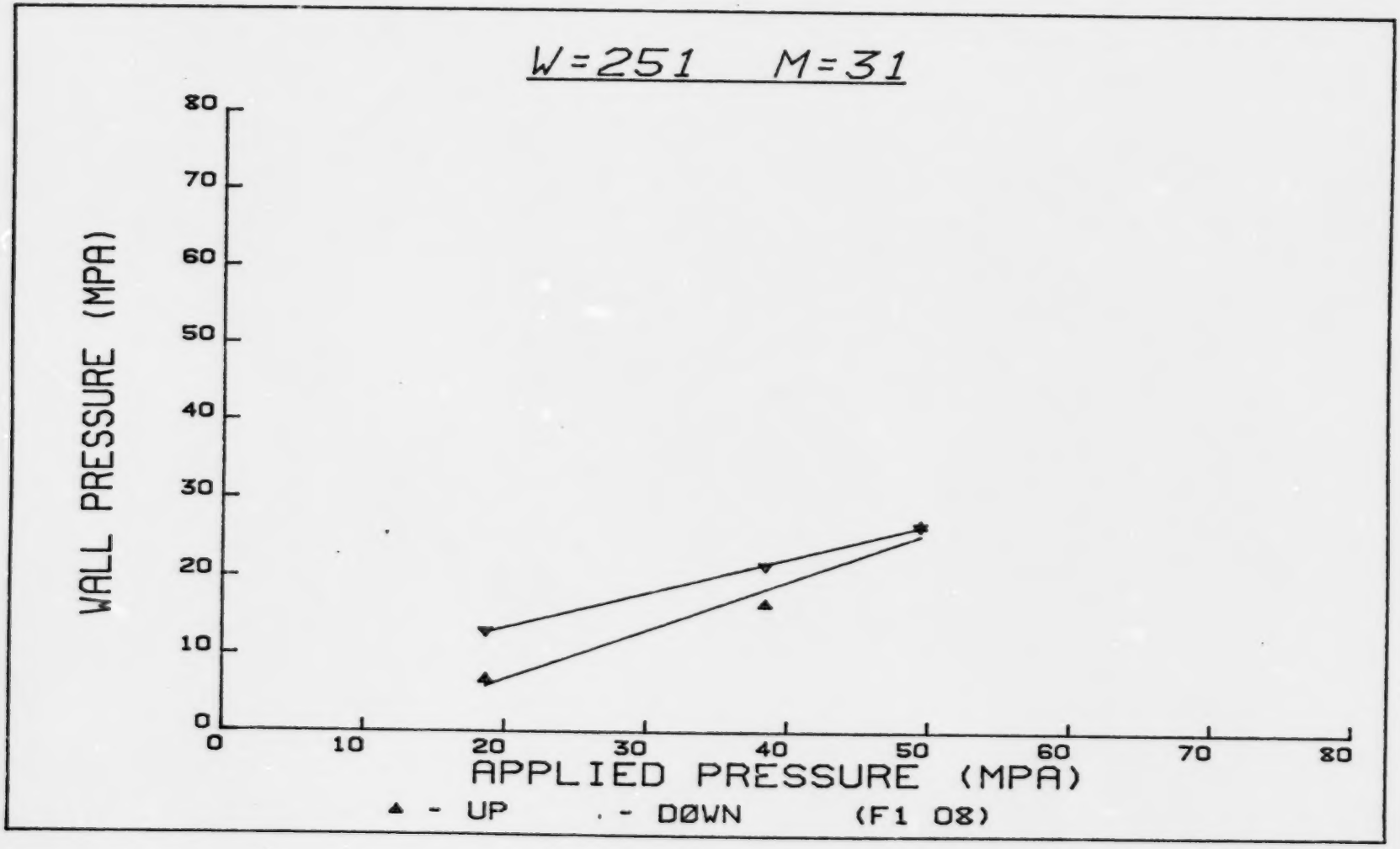
UP $P_w = 2.758 + 0.235\ P_a$

DOWN $P_w = 3.796 + 0.221\ P_a$



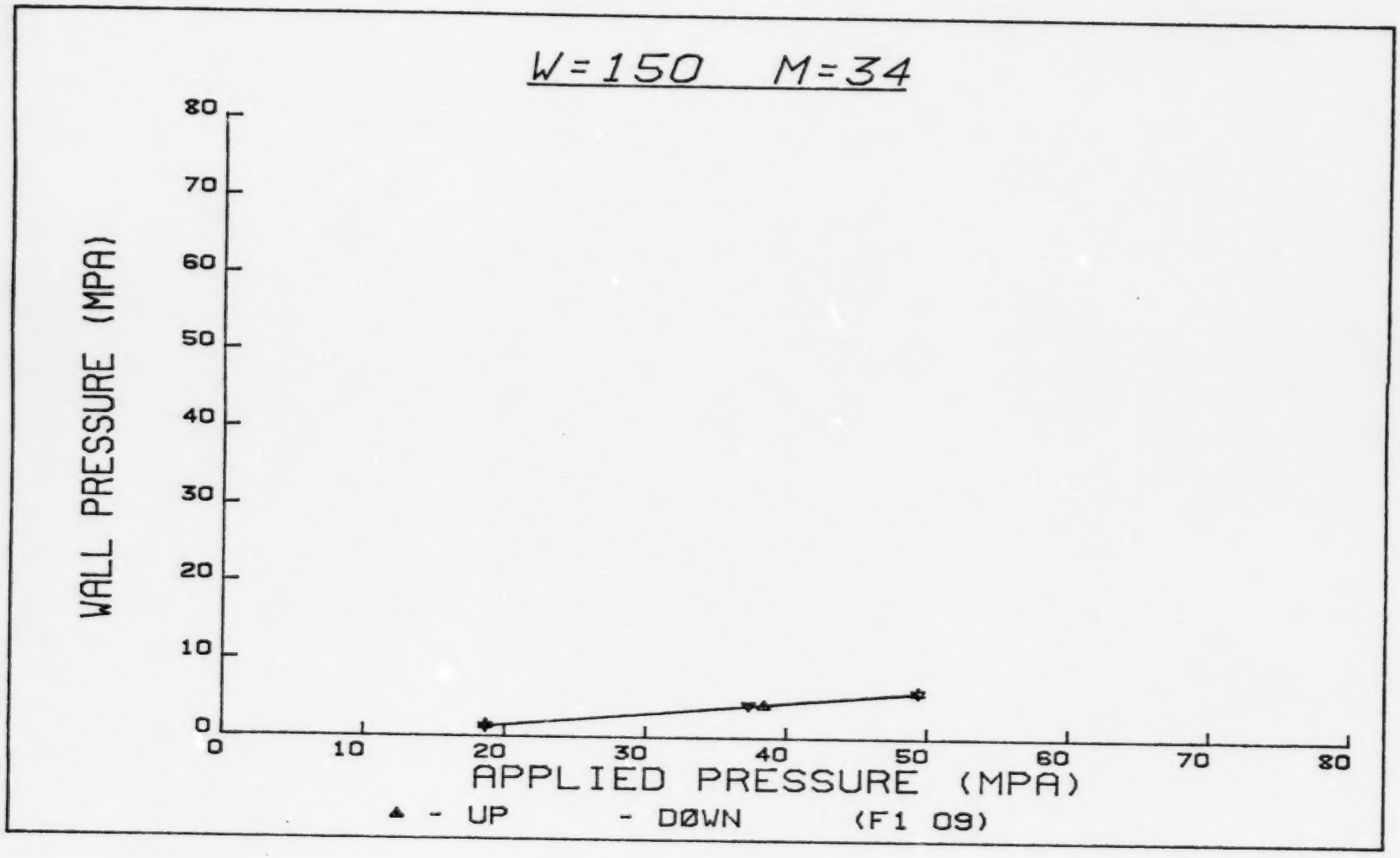
UP $P_w = -5.813 + 0.630\ P_a$

DOWN $P_w = 4.587 + 0.442\ P_a$



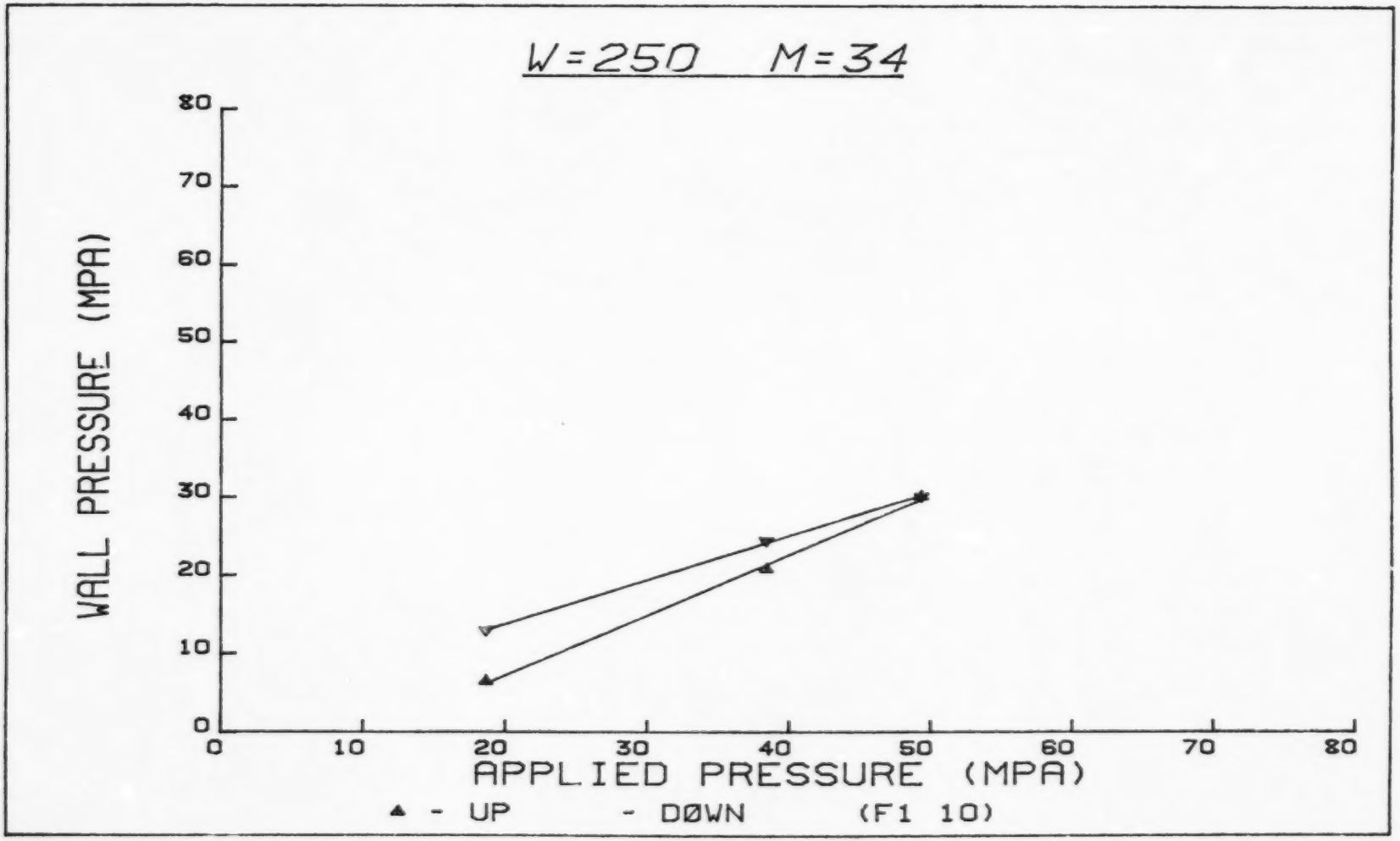
UP $P_w = -1.439 + 0.149\ P_a$

DOWN $P_w = -1.547 + 0.153\ P_a$



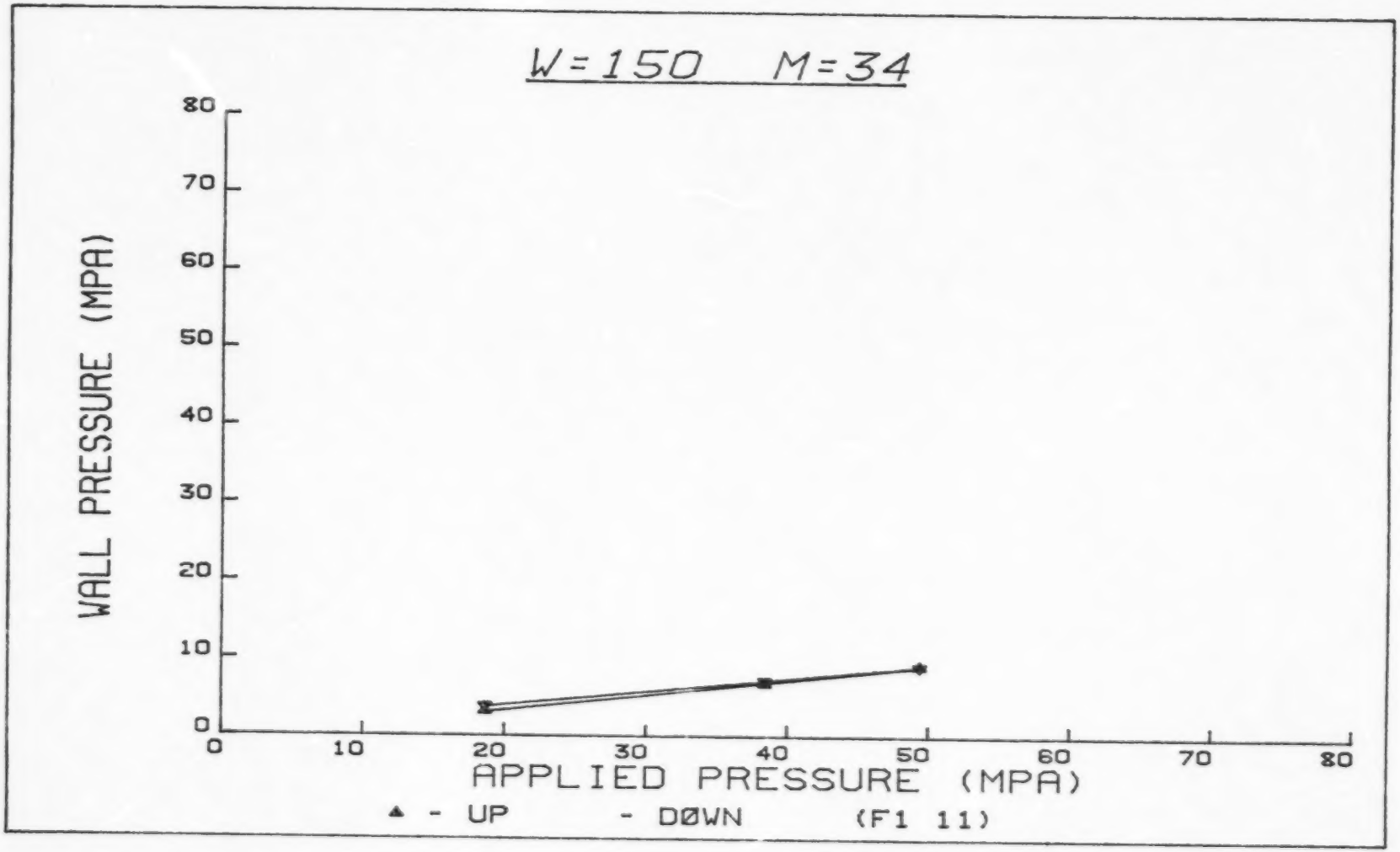
UP $P_w = -7.980 + 0.763\ P_a$

DOWN $P_w = 2.687 + 0.557\ P_a$



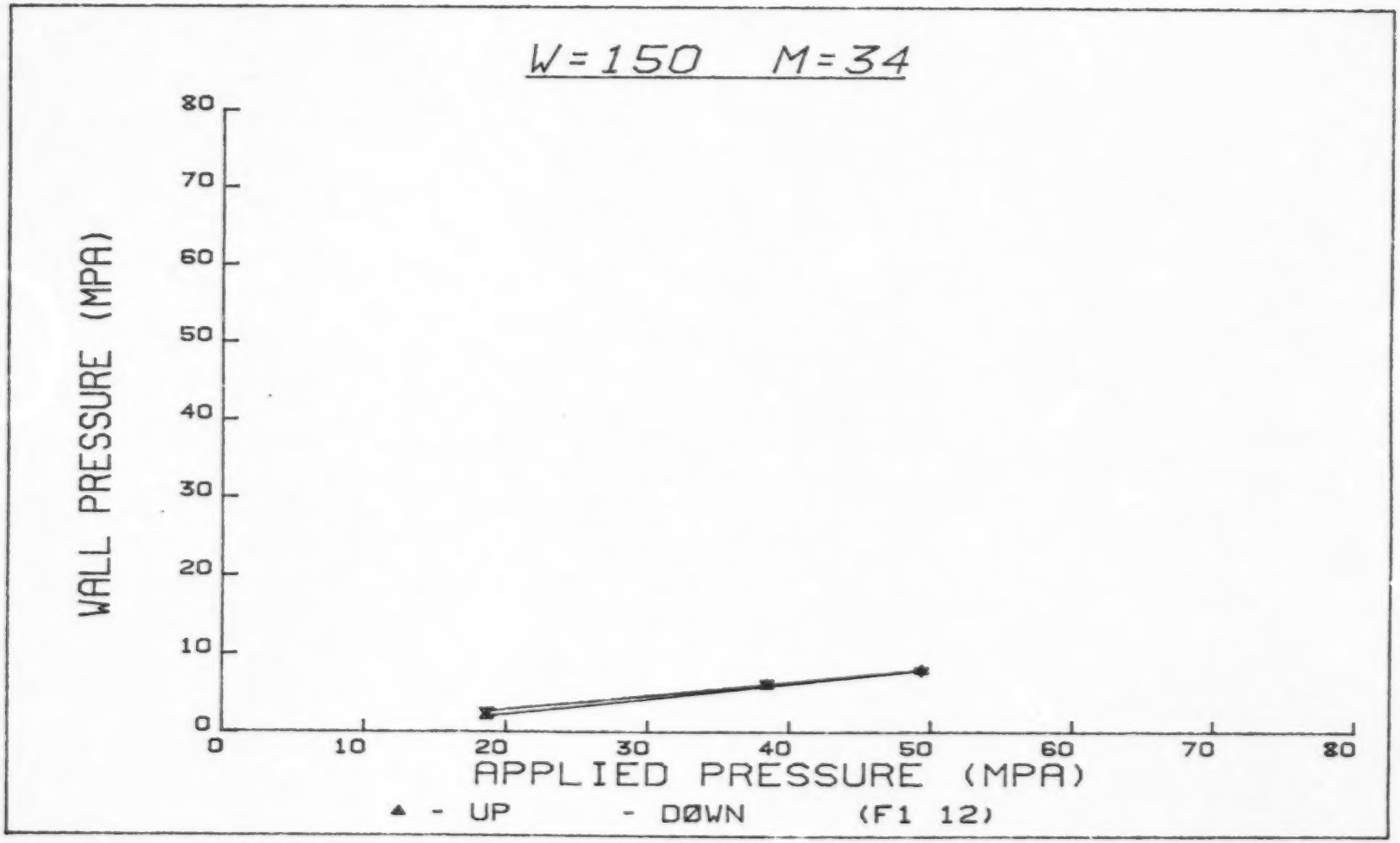
UP $P_w = -0.529 + 0.194\ P_a$

DOWN $P_w = 0.529 + 0.174\ P_a$



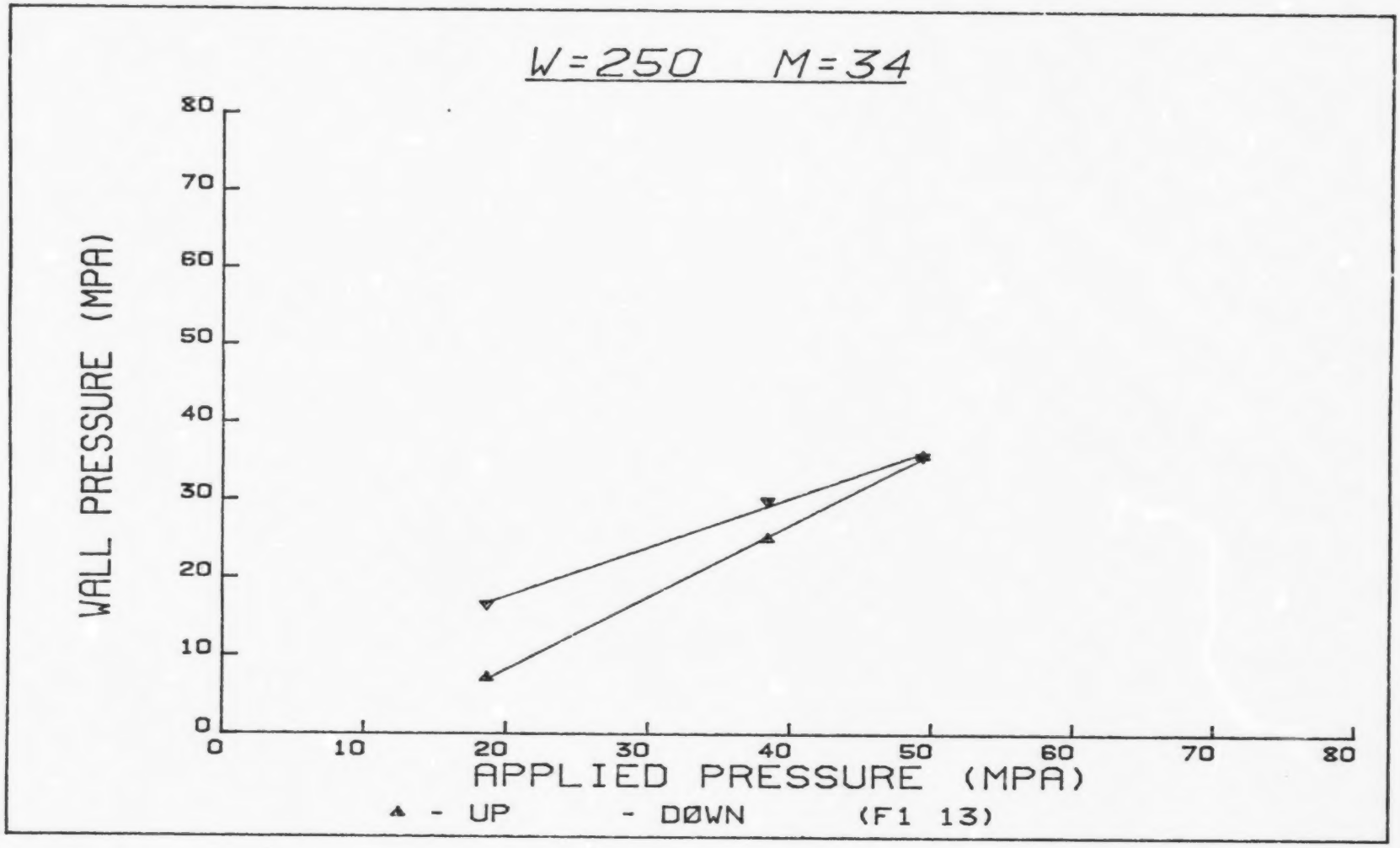
UP $P_w = -1.533 + 0.193\, P_a$

DOWN $P_w = -0.491 + 0.192\, P_a$



UP $P_w = -10.362 + 0.930\ P_a$

DOWN $P_w = 4.930 + 0.634\ P_a$



BOTTOM FORCE VS APPLIED FORCE

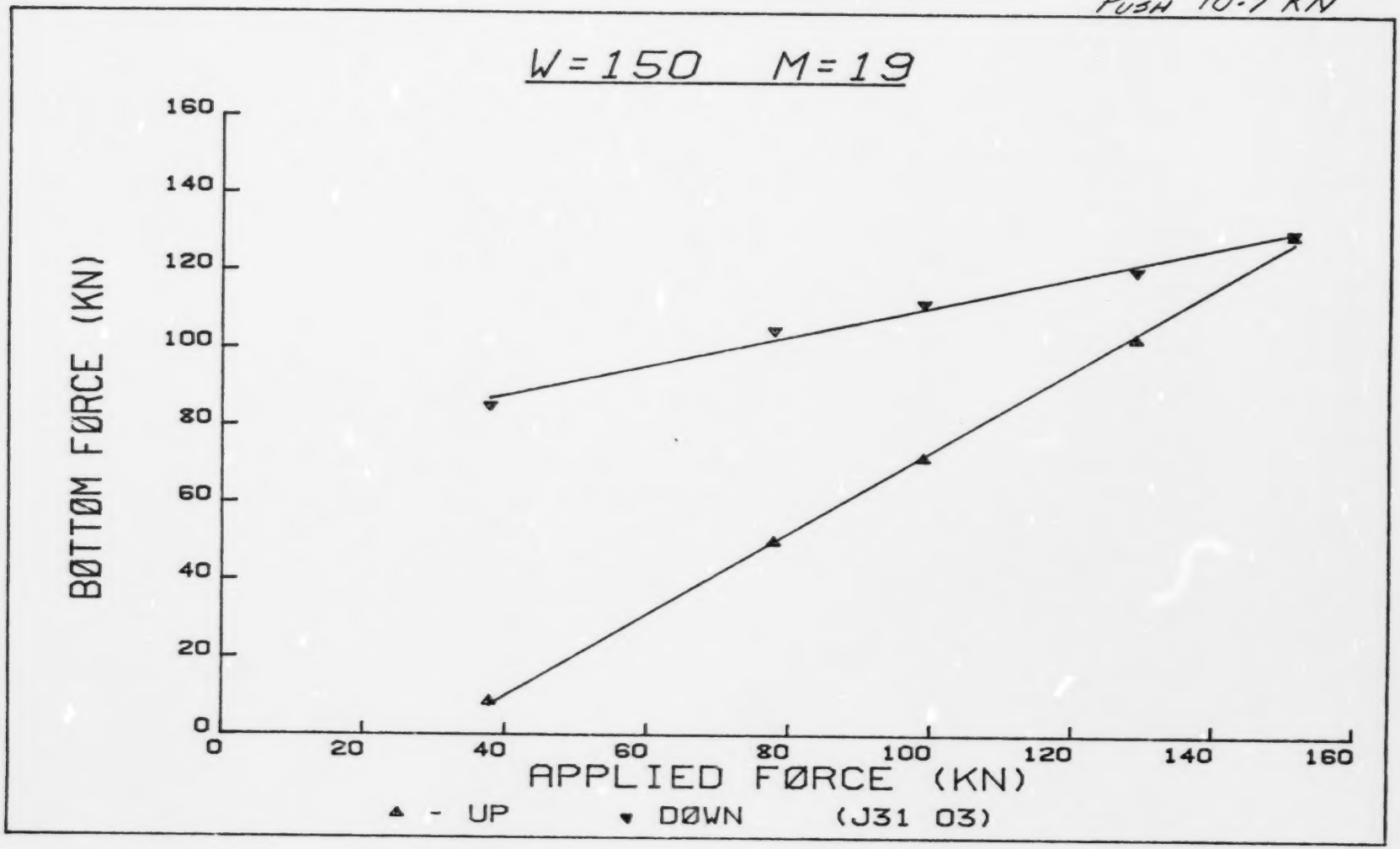
500mm TUBE

(RELEASE FORCE NOTED)

UP $F_B = -32.181 + 1.057 F_a$

DOWN $F_B = 72.492 + 0.384 F_a$

PUSH 10.7 KN

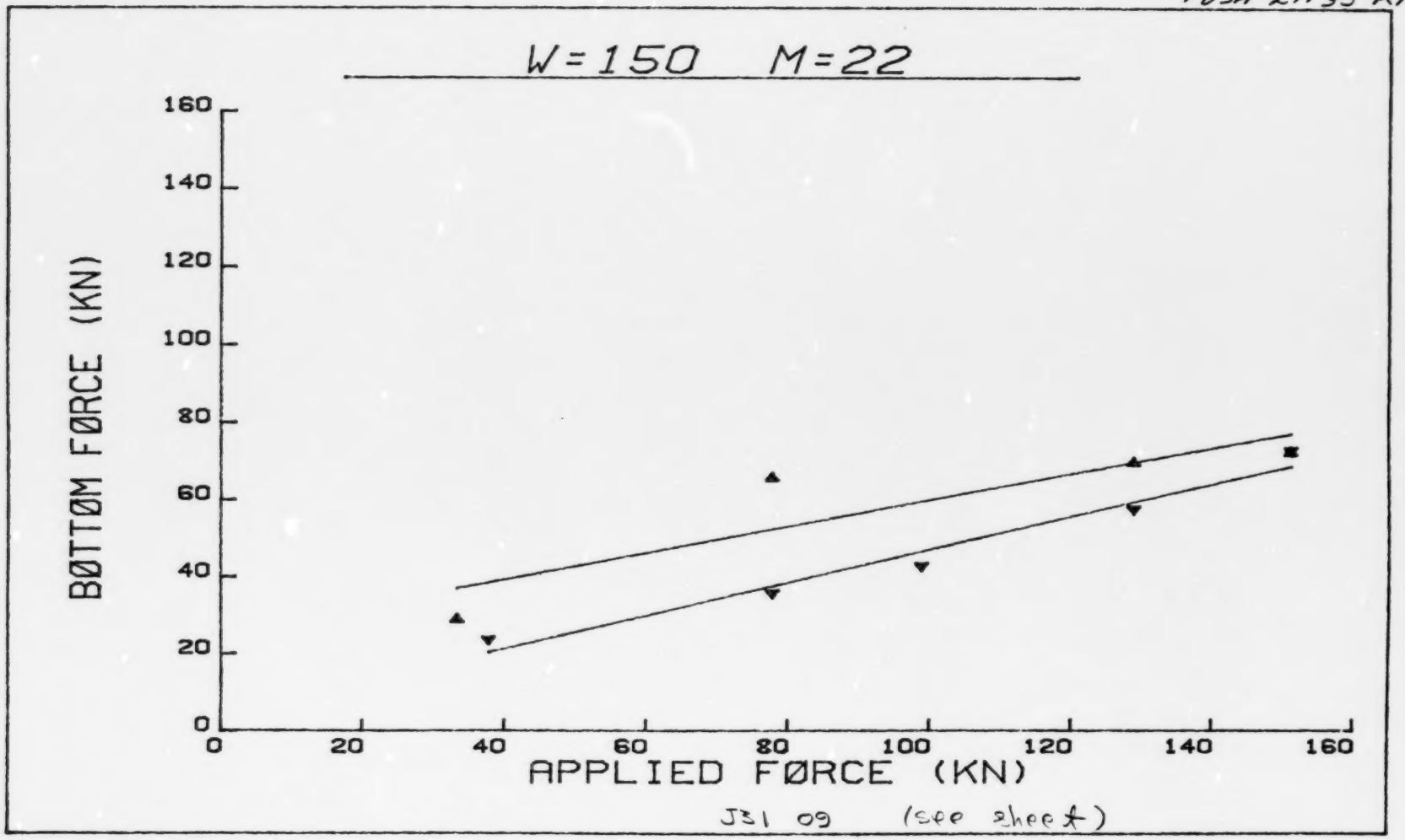


PUSH 21.35

UP $F_B = 25.678 + 0.342 F_a$??

DOWN $F_B = 4.235 + 0.428 F_a$

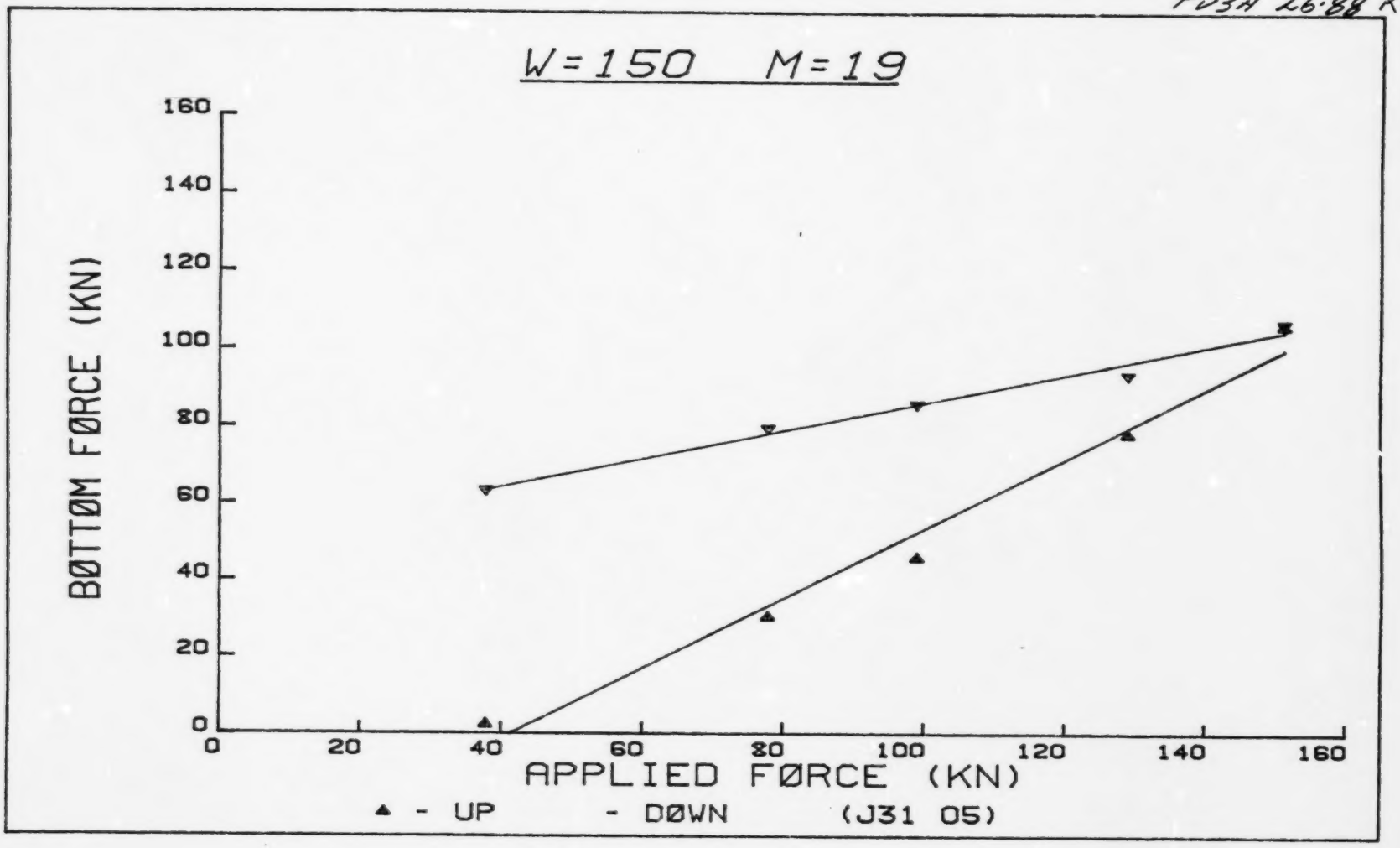
PUSH 21.35 KN



UP $F_B = -37.610 + 0.911\ F_a$

DOWN $F_B = 19.666 + 0.365\ F_a$

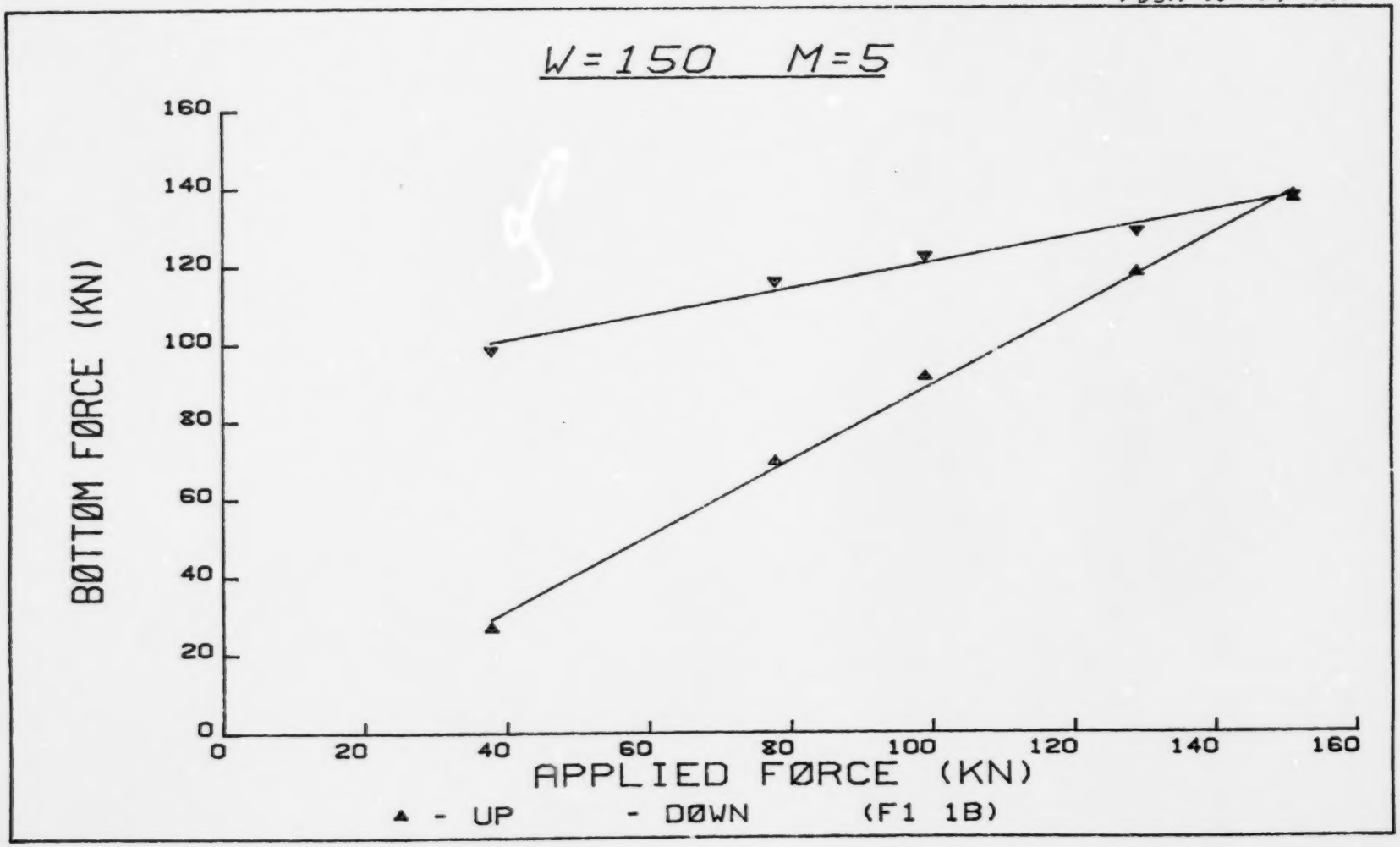
P_{U3H} 26.88 KN



UP $F_B = -7.599 + 0.972\ F_a$

DOWN $F_B = 87.836 + 0.333\ F_a$

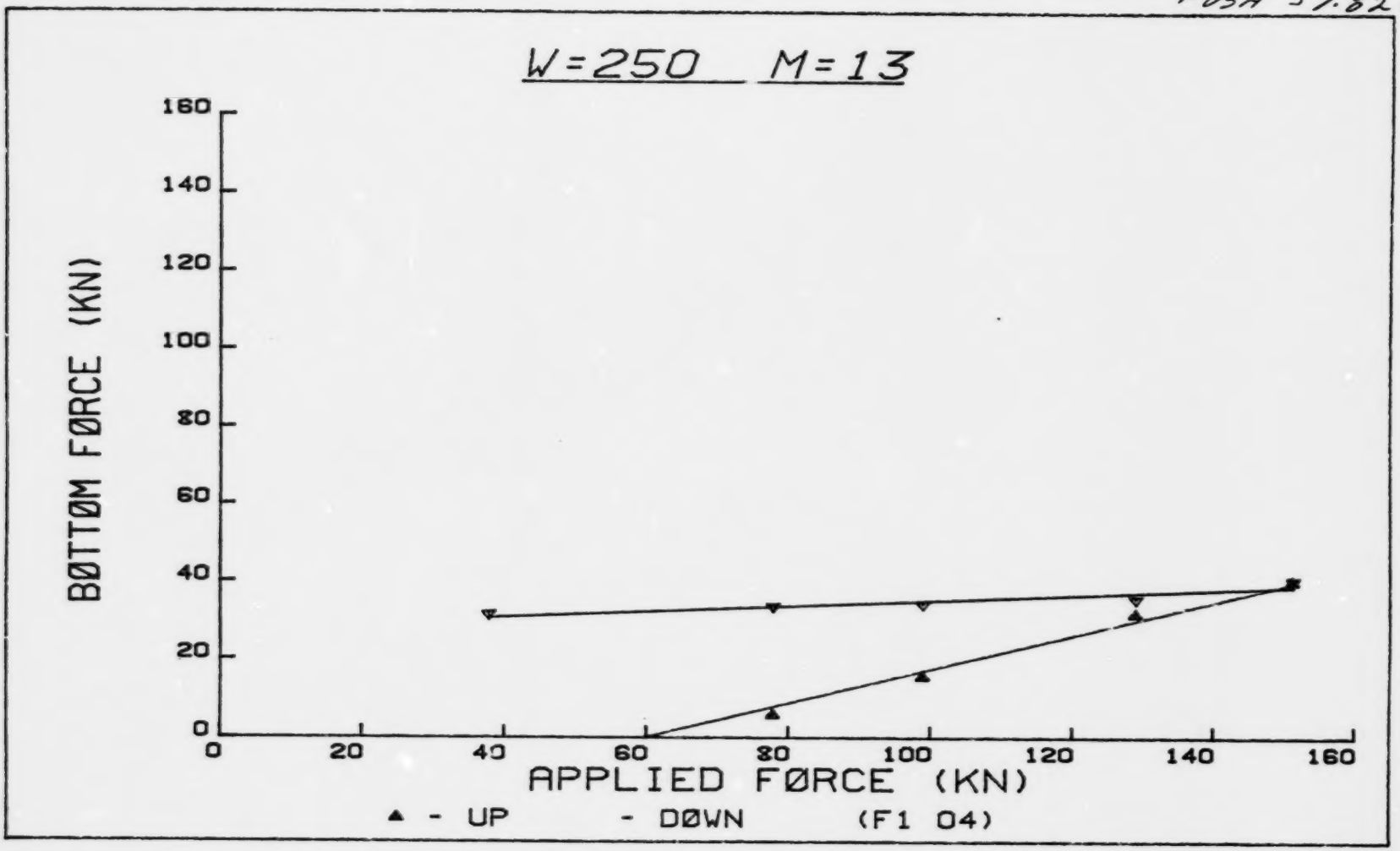
PUSH 26.69 KN



UP $F_B = -25.902 + 0.434\ F_a$

DOWN $F_B = 28.024 + 0.072\ F_a$

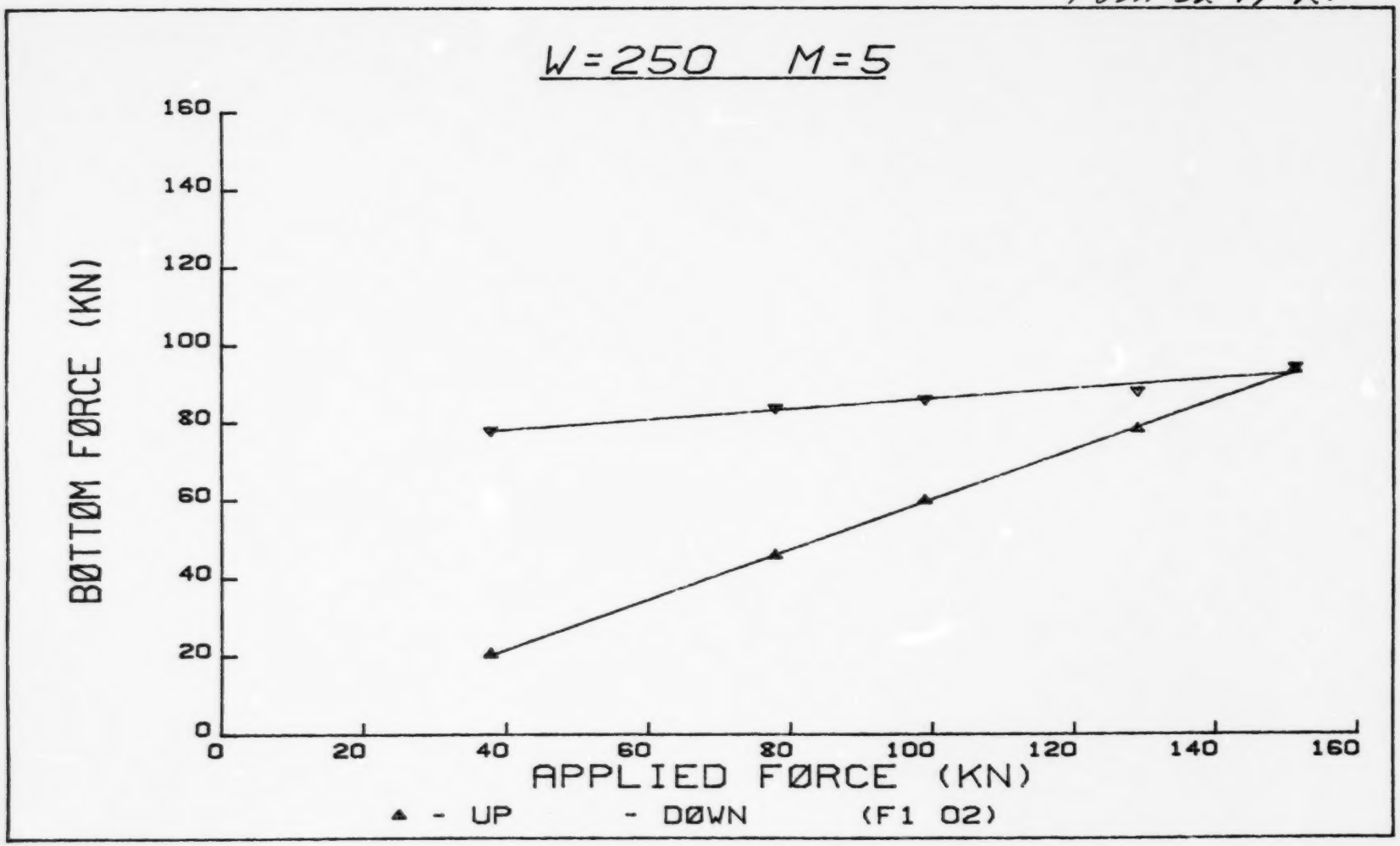
PUSH 57.82 KN



UP $F_B = -3.936 + 0.641\ F_a$

DOWN $F_B = 72.952 + 0.131\ F_a$

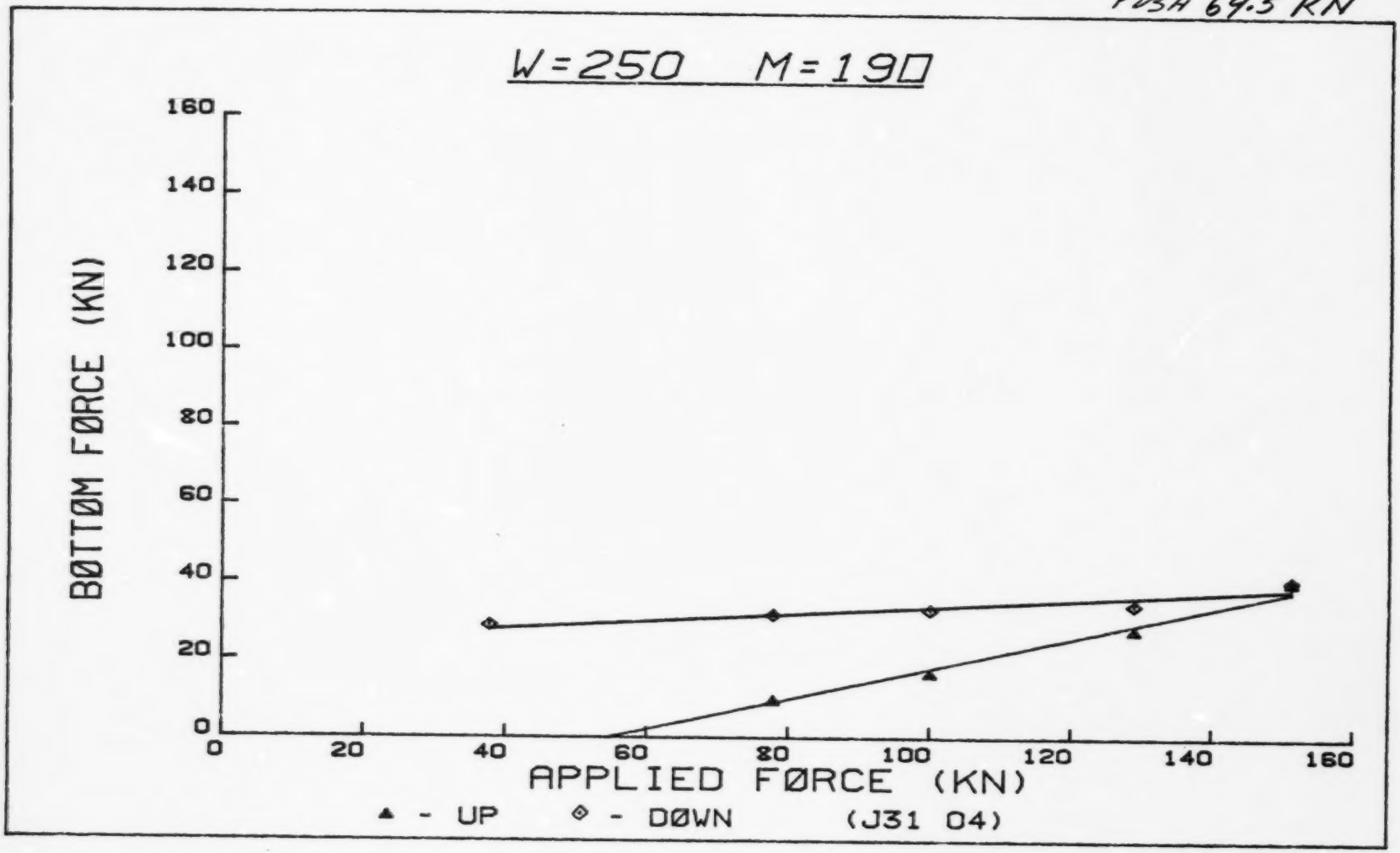
PUSH 52.49 KN



UP $F_b = -21.371 + 0.392\ F_a$

DOWN $F_b = 24.248 + 0.094\ F_a$

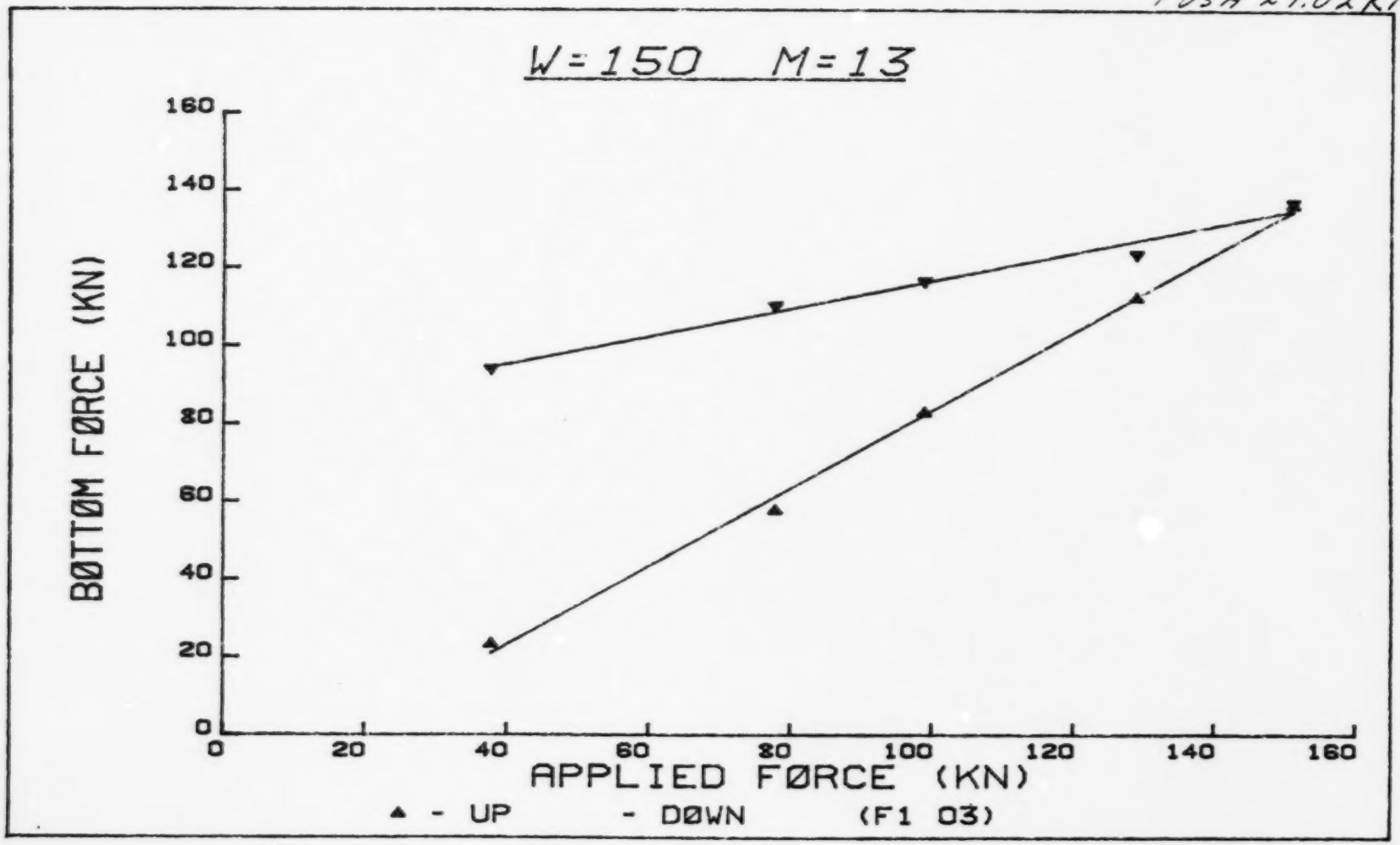
PUSH 64.5 KN



UP $F_B = -16.957 + 1.006\, F_a$

DOWN $F_B = 81.161 + 0.358\, F_a$

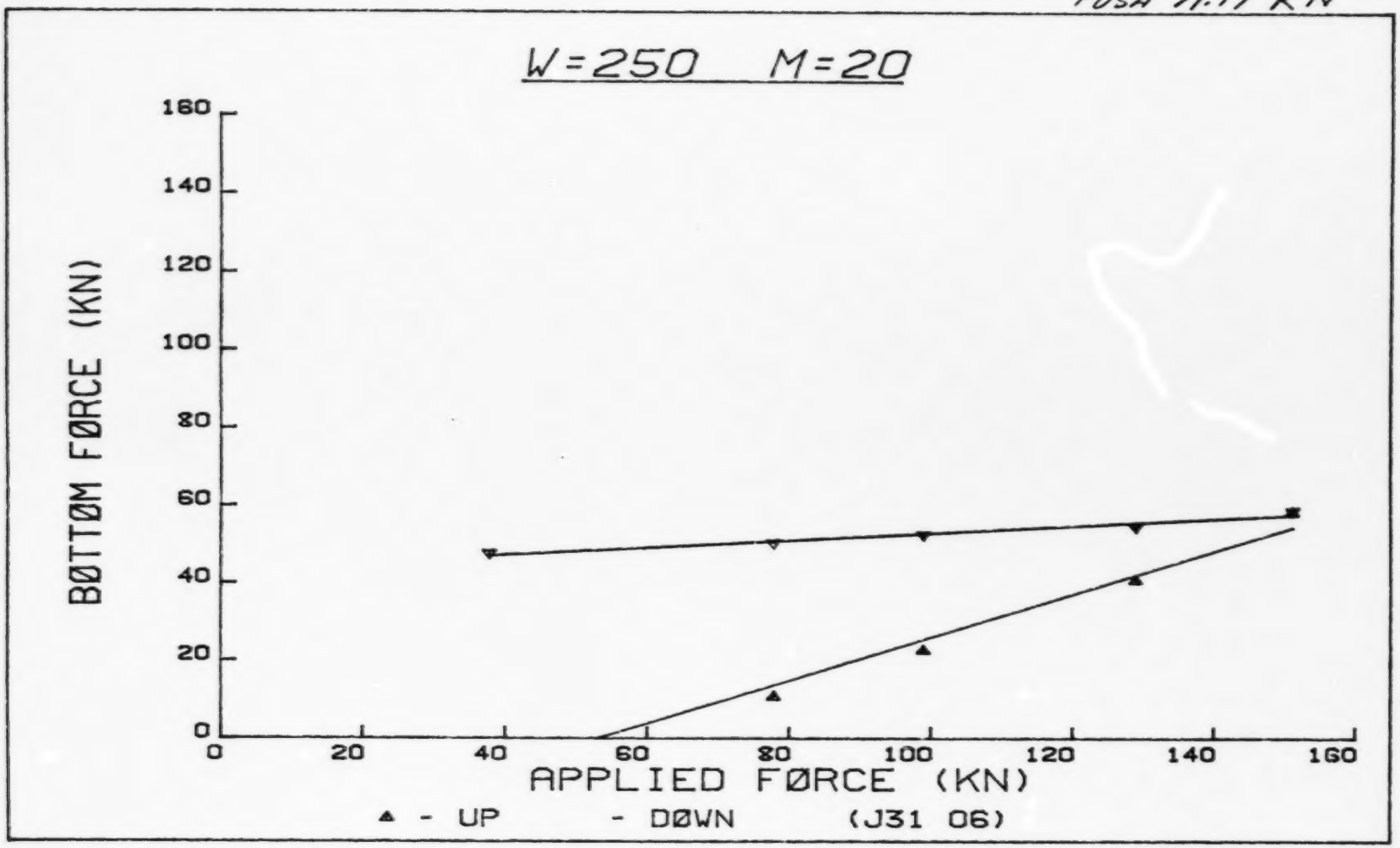
PUSH 24.02 KN



UP $F_B = -29.535 + 0.556\ F_a$

DOWN $F_B = 43.518 + 0.095\ F_a$

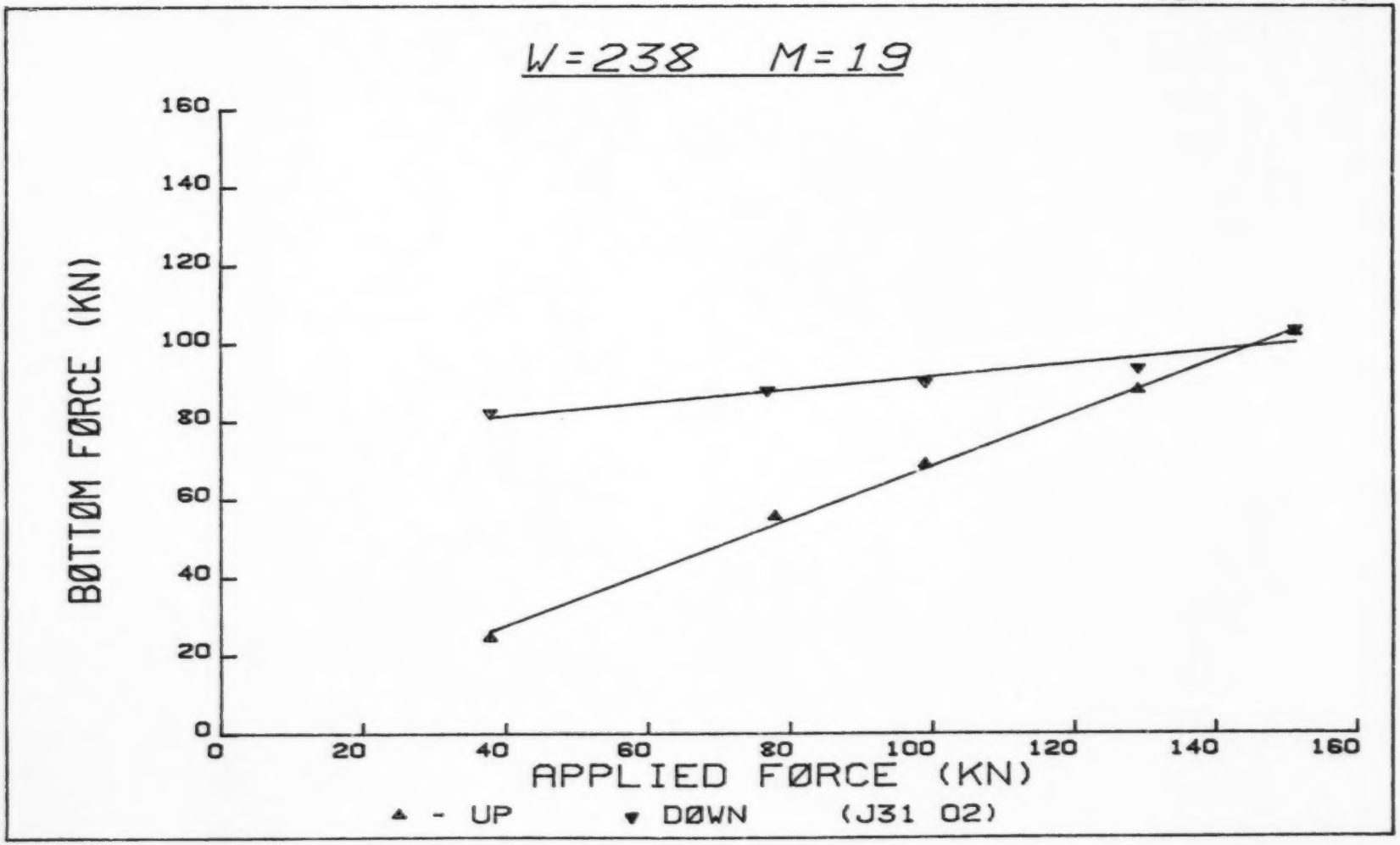
PUSH 71.17 KN



UP $F_b = 0.610 + .681 F_a$

DOWN $F_b = 74.742 + 0.169 F_a$

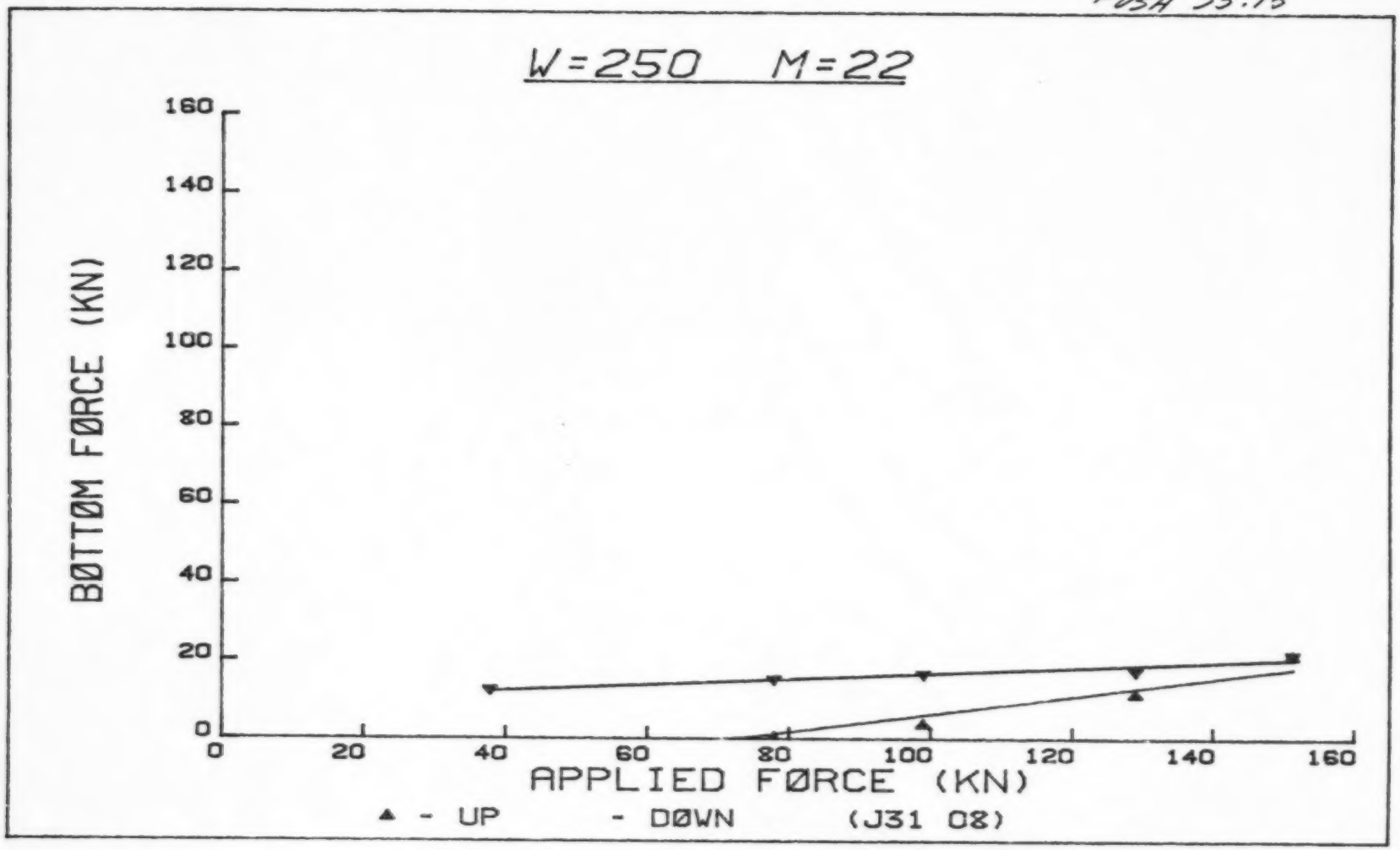
PUSH 44.4 KN



UP $F_B = -16.441 + 0.228\ F_a$

DOWN $F_B = 9.459 + 0.073\ F_a$

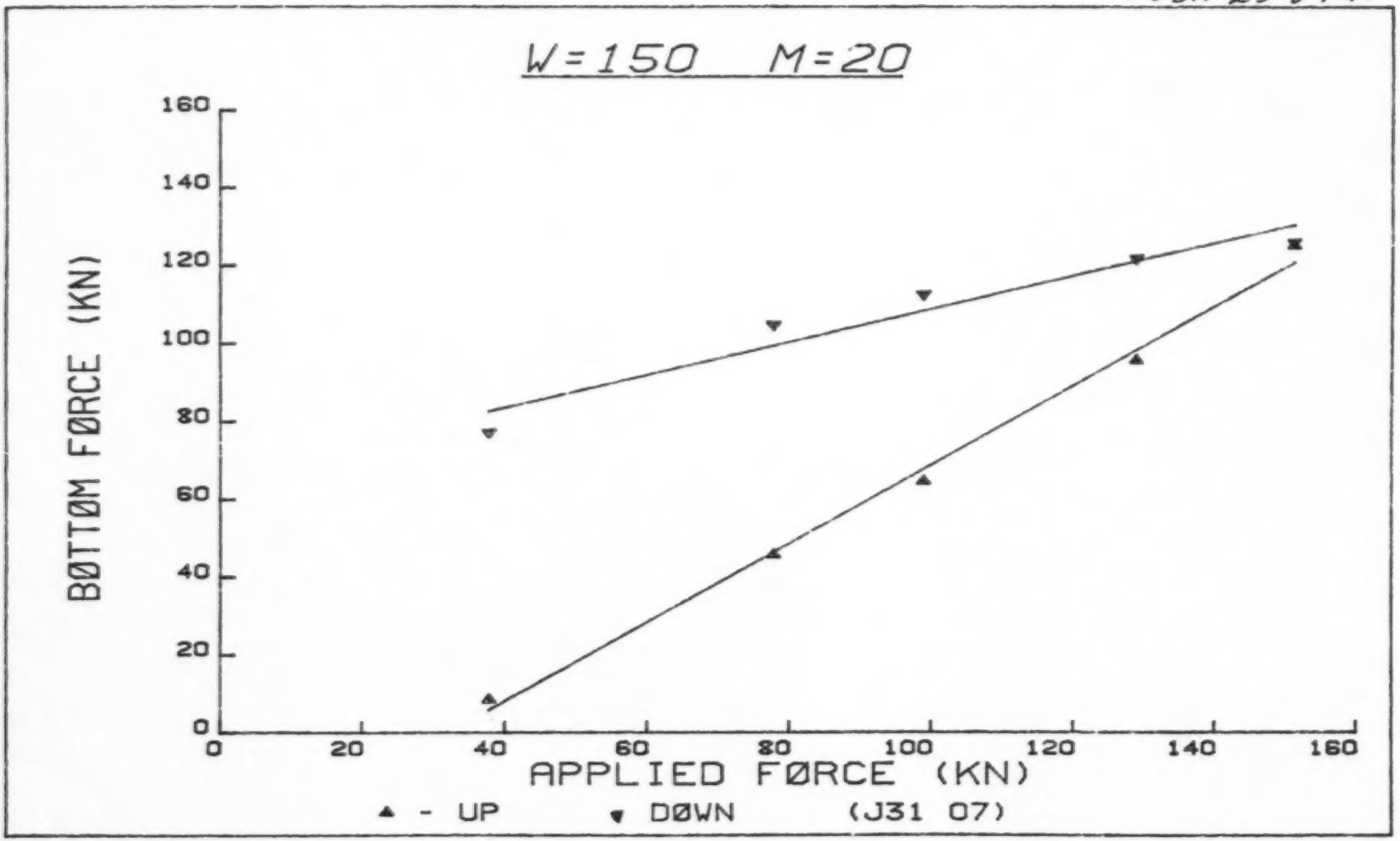
PUSH 55.15



UP $F_B = -32.346 + 1.014\ F_a$

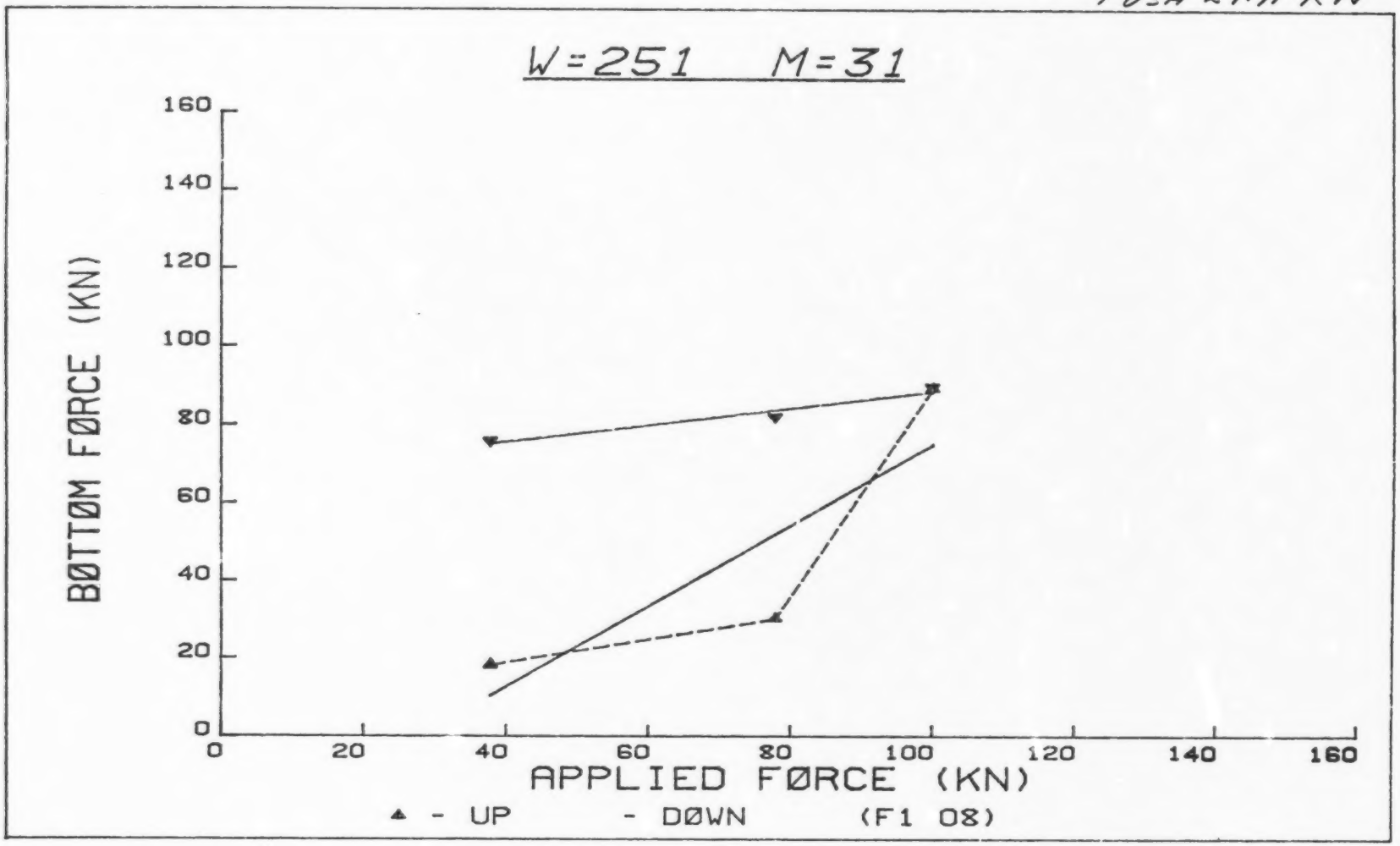
DOWN $F_B = 66.773 + 0.422\ F_a$

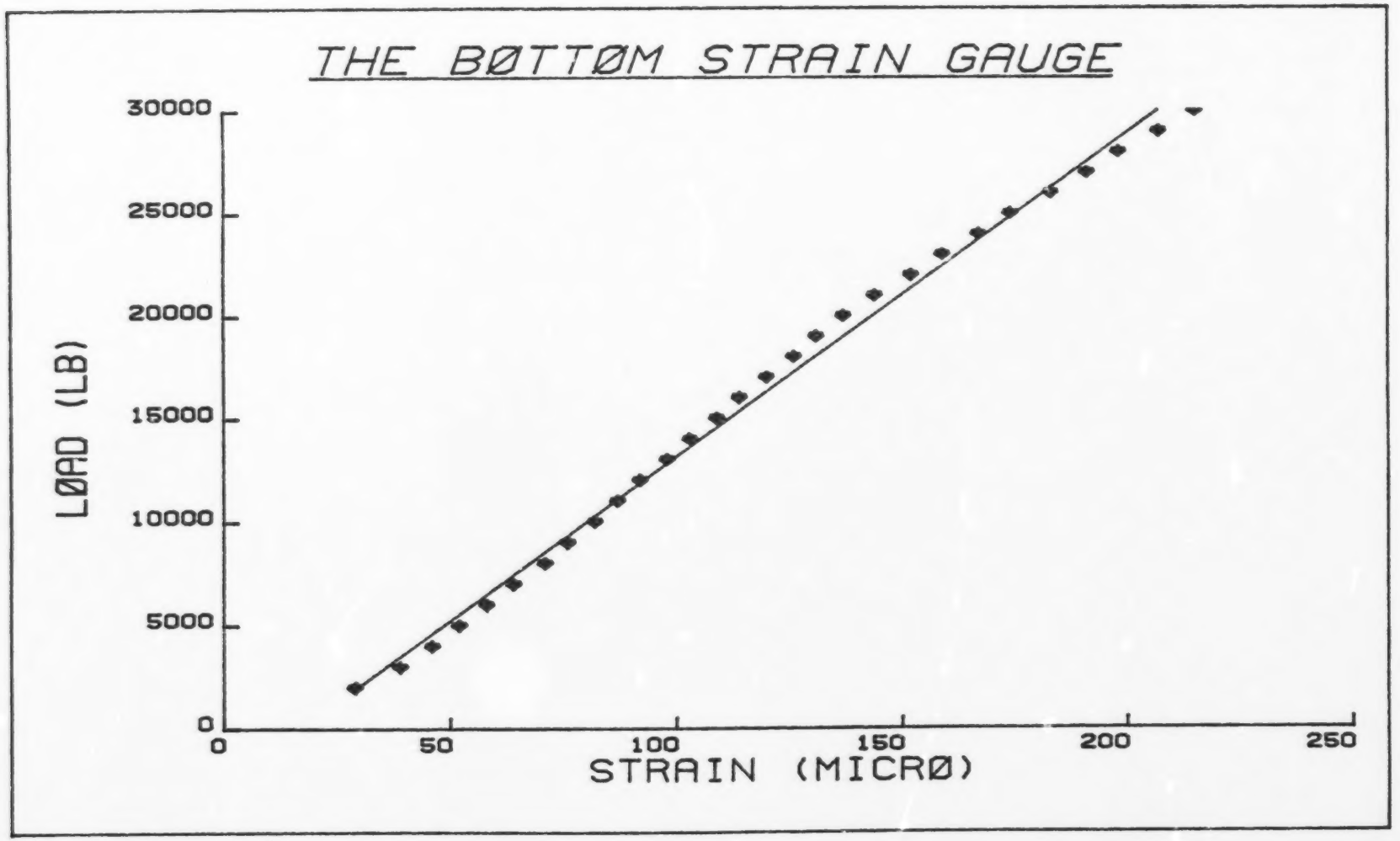
PUSH 25.8 KN



DOWN $F_B = 67.019 + 0.218\ F_a$

PUSH 24.91 KN




THE BØTTØM STRAIN GAUGE
30000
25000
20000
15000
10000
5000
0
LØAD (LB)
0
50
100
150
200
250
STRAIN (MICRØ)